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# ENERGY DISSIPATION BY CASCADES

by

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A THESIS
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## ABSTRACT

This thesis summarizes an investigation of the ability of artificial cascades to dissipate energy of flow, and attempts to establish some design criteria for their use on spillway structures.

Artificial cascades were produced by running water over steps of various shapes and sizes, installed on the floor of a laboratory flume. The energy dissipating ability of a particular cascade was compared with that of others by measuring the energy of flow in a horizontal stilling basin at the downstream end of the flume. Thus knowing also the total energy upstream, the energy loss on the flume was known and was compared with the energy loss produced by other cascades.

A total of eighty-eight test runs was made using a total of ten roughness spacings. The slope of the flume was not changed for any of these tests. Apparatus used and the experimental techniques are described in detail. A dimensional analysis is presented and the experimental results have been applied to the resulting parameters in an attempt to see if correlation between them exists.

Results indicate that cascades can dissipate a substantial amount of energy of flow. It appears that for a given shape and arrangement of steps, the amount of energy dissipated by cascades is dependent upon the number of steps used, up to a limiting number. Above this limiting number, the cascades produced will dissipate a decreasing amount of energy. For a given step design the resulting flow in the downstream stilling basin has been defined by an equation of the form $d = \frac{d_c^{m} . H_T^{n}}{C}$. An example design of a canal drop structure using a cascade to dissipate energy is given.

# ACKNOWLEDGEMENT

The author wishes to express his thanks to Professor A. Peterson, who supervised the research and the writing of the thesis. His guidance and suggestions were most welcome. Professor T. Blench gave valuable suggestions for the presentation of experimental results. Professor N. Rajaratnam offered many sources of information. Mr. R. Eckman and the staff at the Graduate Hydraulics Laboratory provided excellent help in the construction of equipment, and were always on hand to provide assistance when needed. To these persons the author expresses his sincere thanks.

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# CHAPTER I

## INTRODUCTION

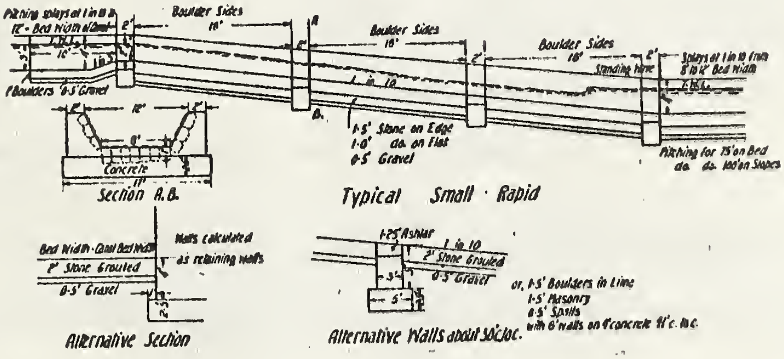
1.1 A design problem in many river development structures is ensuring that water passing through a spillway reaches the downstream channel with minimum energy of flow. A method neglected in current practice for dissipating energy of flow is the one whereby a cascade or a series of steps is developed down the spillway chute. In nature, cascades are exemplified by rapids in a river. They are copied in engineering by making the spillway of boulders or concrete blocks; such a structure is often called a "rock rapid". The standard, modern methods used to dissipate energy are (i) to provide a stilling basin that will develop a hydraulic jump (ii) to assist the formation of a hydraulic jump in the stilling basin by blocks placed at the base of the spillway chute (iii) to create a "ski-jump", so that the flow down the chute hits the downstream channel far enough from the hydraulic structure for the resultant scour hole to be of little consequence. As a long and deep stilling basin can be very expensive, and as rock rapids demonstrate that cascades can appreciably reduce the size of stilling basin required, there is reason to expect that artificial cascades could be of practical value.

1.2 Therefore the author decided to make a preliminary investigation

of the potential of cascades as an energy dissipator, and to attempt to formulate some design criteria for them.

1.3 A literature investigation revealed the following cases:

(i) Parker, (1913) outlined the use of "rock-rapids" in a drop structure in a canal system in India. The chute floor and walls of the drop are roughened by finishing off these surfaces with boulders. It is stated that these drops be built on a slope of 1:10, which was arrived at by experience since "a steeper slope is accompanied by excessive erosion downstream". A typical arrangement on the chute floor (FIGURE 1.1), is to have 1½ foot stone placed on edge and grouted and set on a 2½ foot concrete pad. The walls may consist of 1½ foot stone



TYPICAL CANAL SECTION FOR DEVELOPING ROCK RAPIDS (After Parker, 1913)

FIGURE 1.1

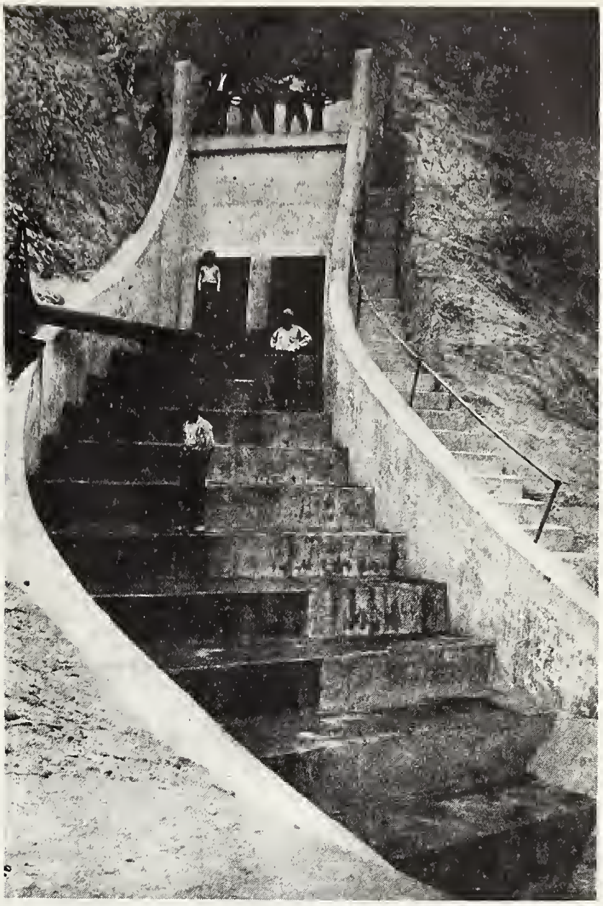
set in concrete. This roughened canal section is carried downstream of the drop for 75 feet, with the result that a cascade is developed on the chute, and a hydraulic jump forms at the base of the drop. The energy-dissipating ability of this system was very satisfactory.

(ii) Heinly, (1915) described the use of a curved chute which was a section of an aqueduct in an irrigation canal. In a vertical drop of 22 feet in a distance of 44 feet, a design discharge of 23.6 cusecs per foot* flowed over eleven steps each having a height of two feet and a width equal to the width of the chute, (PHOTOGRAPH 1.1). The designed sidewall height is four feet. No design criteria or performance data are given.

(iii) Etcheverry, (1916), PHOTOGRAPH 1.2 deals with a structure which is part of a canal drop, and shows the flow on it to be operating as a free overfall from step to step. Velocity of flow on each step appears to be subcritical or not much above critical, and also obvious is the apparent large increase in air entrainment as flow progresses downstream.

(iv) Gausmann and Madden, (1923), described the problems encountered in the design of a stepped, overfall dam and its

*"cubic feet per second" per foot width of channel, abbreviated to "cusecs" per foot



STEPS USED TO DEVELOP A CASCADE ON A SPILLWAY CHUTE
[After heinly, 1915]

PHOTOGRAPH I.I

EXAMPLE OF A CASCADE BEING USED IN A CANAL DROP
[ After etcheverry, 1916]

PHOTOGRAPH I. 2

[illegible]

[illegible]

[illegible]

[illegible]

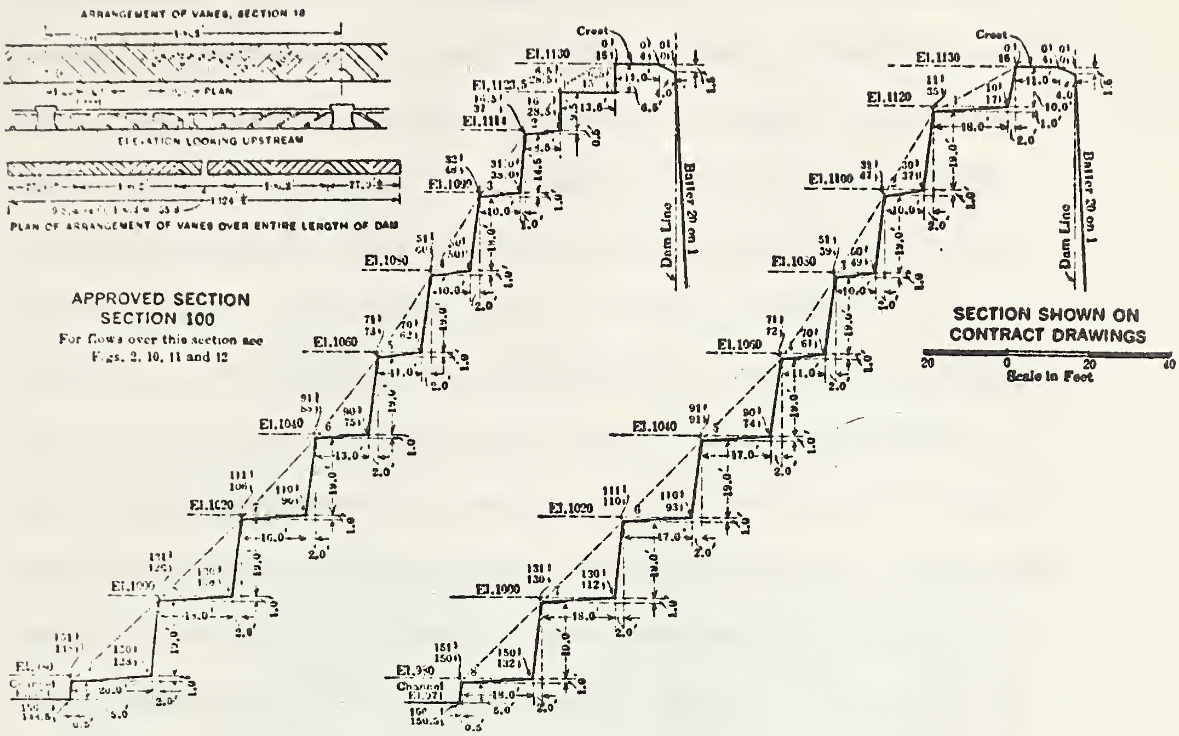

ARRANGEMENT OF VANES, SECTION 10
PLAN
ELEVATION LOOKING UPSTREAM
PLAN OF ARRANGEMENT OF VANES OVER ENTIRE LENGTH OF DAM
APPROVED SECTION
SECTION 100
For flows over this section see Figs. 2, 10, 11 and 12
Crest
El.1130
El.1120
El.1100
El.1080
El.1060
El.1040
El.1020
El.1000
Channel
Dam Line
Batter 20 on 1
SECTION SHOWN ON CONTRACT DRAWINGS
20
0
20
40
Scale in Feet

FIGURE 1.2 SECTION OF STEPPED OVERFALL DAM ~~AND~~ PLAN OF VANES USED ON FIRST STEP [AFTER GAUSMANN AND MADDEN, 1923]

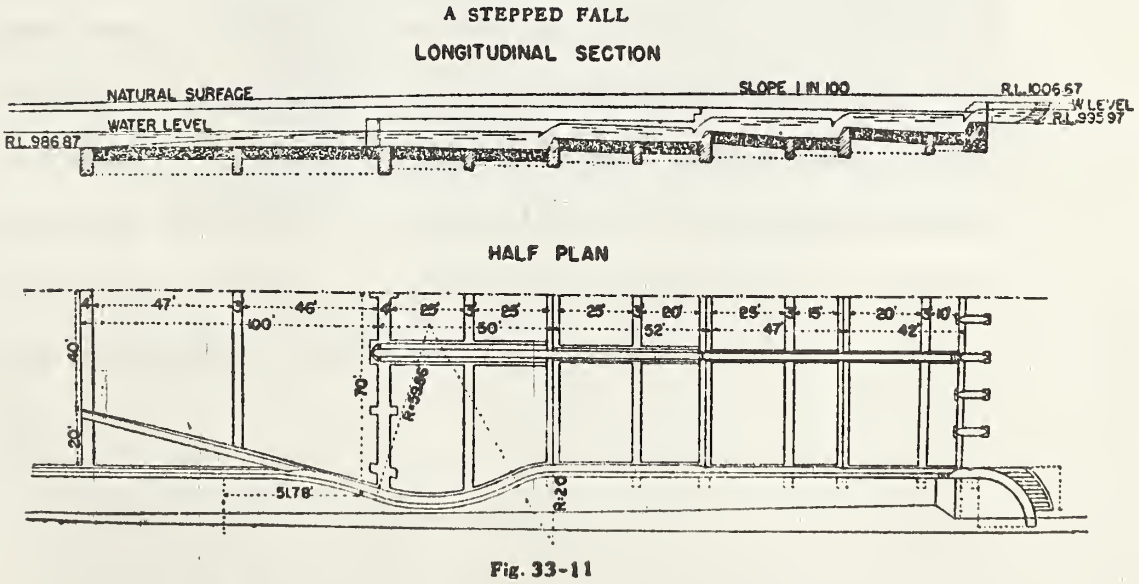
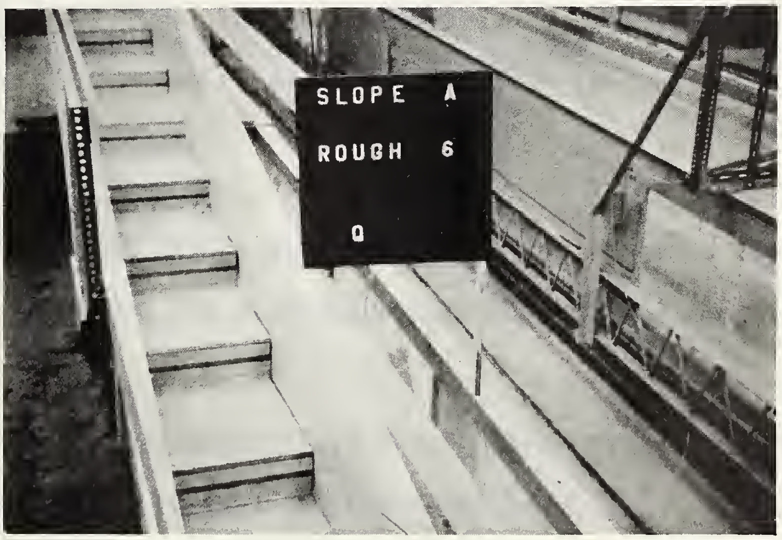


FIGURE 1.3 SECTION OF CANAL DROP USING BACKSLOPED STEPS [AFTER KHUSHALANI, 1954]

associated spillway channel. This dam consists of a 1000 foot length of earth dike and a 1324 foot length masonry section. The down-stream side of the masonry overfall section is partly formed of a continuous series of steps, having a total drop of 160 feet. Model experiments were carried out in order to check the design capacity of the spillway channel, and to find a stepped section which would satisfactorily dissipate the energy of the overfall sheet. The stepped section chosen is shown in FIGURE 1.2, and consists of steps varying in height from eleven feet at the top to nineteen feet at the bottom. Approximate slope of the downstream side of the overfall section is 1:1 and design discharge is 83 cusecs per foot on the crest. In the final design it was found necessary to construct vanes on the first step (FIGURE 1.2), which were needed to improve the break-up of the falling sheet of water.

(v) Khushalani, (1954), described the use of a stepped canal drop, FIGURE 1.3. One such structure has a total fall of 53.5 feet divided into seven backsloped steps, diminishing from 10.5 feet to 5.5 feet in vertical height. Design discharge is 50 cusecs per foot and the slope is 1:100. As an energy dissipator this design performed extremely well, mainly because a hydraulic jump developed on every step.

1.4 In the above cases it is noted that the cascades were usually developed by using a series of ordinary steps in the spillway chute. The ratio of the average height of step to total design drop varies between 23.6 cusecs. per foot to 83 cusecs. per foot and 1:100 to 1:1, respectively. With the preceeding information as a start, the author decided to select step sizes and shapes that appeared to have been fairly successful and systematize them, with others, into a set of model experiments. Experiments consisted of providing a series of steps in a flume, FIGURE 1.4 and PHOTOGRAPH 1.3, and measuring the total head $H_T$ upstream relative to a floor at the base of the steps, and the total head $E_f$ at the relatively "undisturbed" flow some distance along the base. The difference gave the head loss $H_L$ and the efficiency of energy dissipation was taken as $H_L / H_T$. The various details, auxiliary measures and precautions are described



SERIES OF STEPS IN THE SPILLWAY MODEL - PHOTOGRAPH 1.3

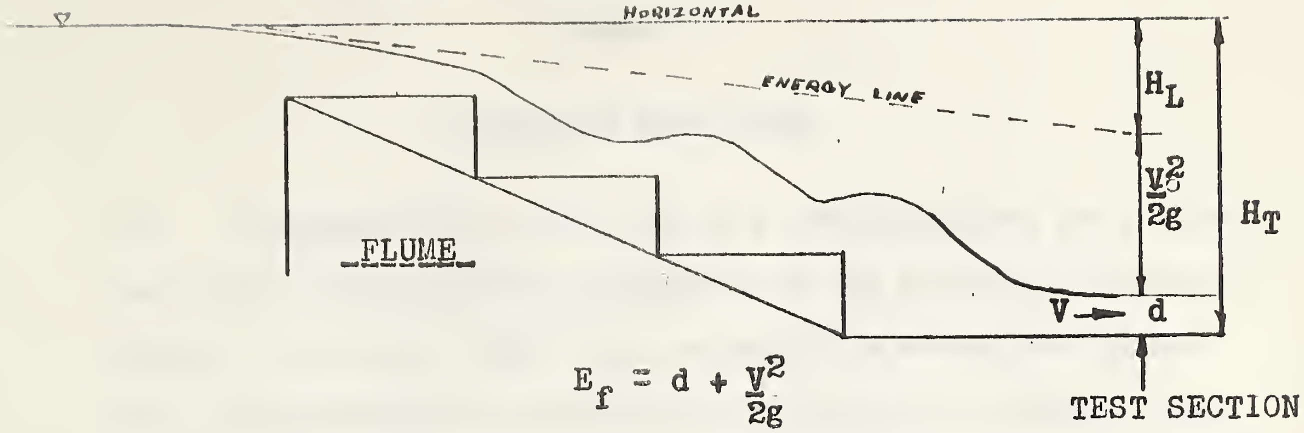
[illegible]

[illegible]

[illegible]

FIGURE 1.4

ENERGY DISSIPATION BY CASCADES



in the following chapters. Results indicate that cascades deserve consideration in the design of an economical energy dissipator.

1.5 **Definition of terms:** The letter symbols adopted for use in this study are found for convenience of reference in APPENDIX A. Descriptive terms are as follows:

(i) Roughness elements: The plywood steps of various sizes and shapes, placed on the floor of the model spillway to develop a cascading type of flow.

(ii) Two-dimensional roughness element: A step which has the same width as the flume of the model spillway.

(iii) Three-dimensional roughness element: A step which is not continuous across the breadth of the flume.

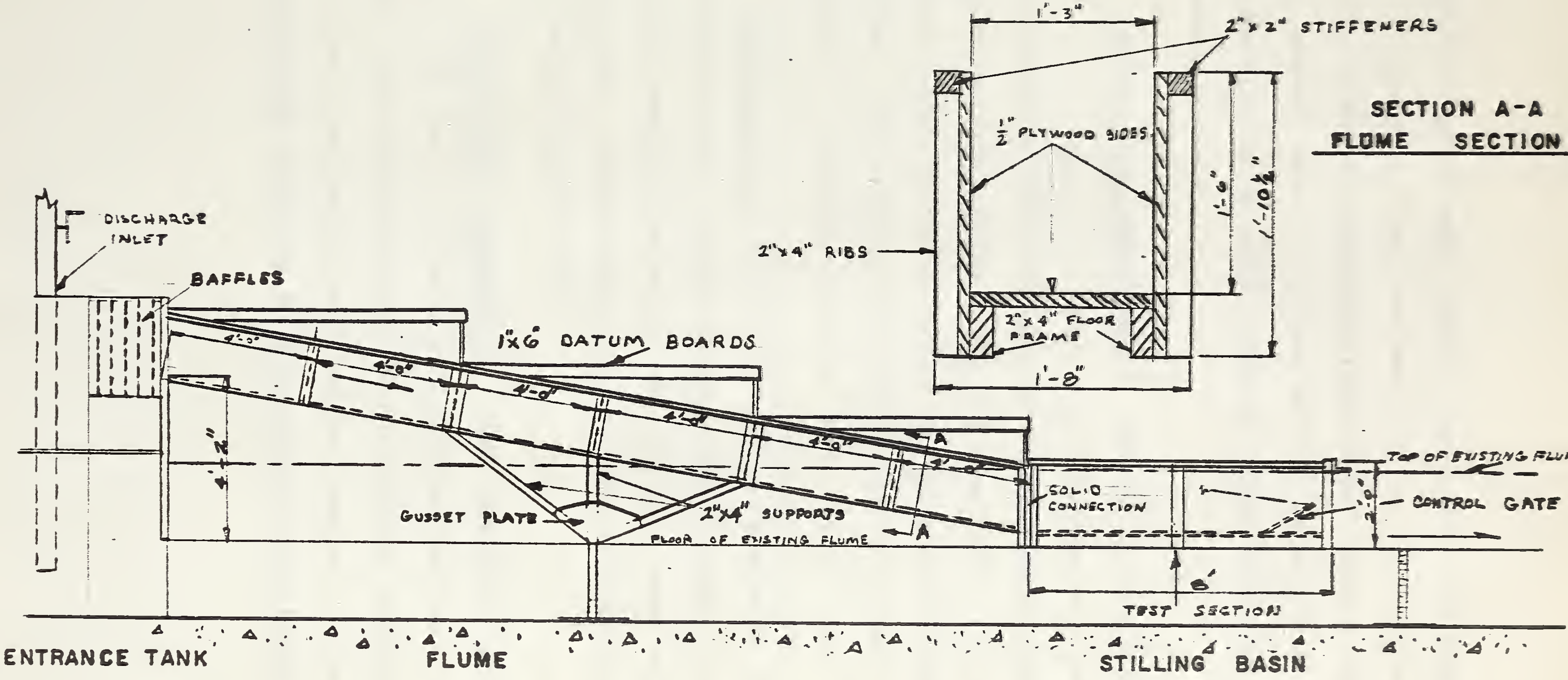
(iv) Roughness spacing: The various arrangements and relative positions which the roughness elements were given on the floor of the model spillway.

# CHAPTER II

# LABORATORY MODEL STUDY

2.1 APPARATUS: The model study of a cascade spillway was carried out in the Graduate Hydraulics Laboratory at the University of Alberta, Edmonton. The model, FIGURE 2.1, consisted of a rectangular plywood flume, PHOTOGRAPH C-1, in which was built a cascade, PHOTOGRAPH C-12, by placing roughness elements on the floor of the test flume, PHOTOGRAPH C-5. A laboratory water supply was used in the operation of the model and was measured by means of an orifice meter and/or a weigh tank. The flow from the supply lines discharged into an entrance tank, where it was stilled by baffles prior to its passage into the model. After passing through the model, the water returned to a sump. The tailwater at the lower end of the model was maintained at any desired depth by means of an adjustable tailwater gate. Point gauges were used for measurements of water-surface elevations, and all velocity measurements were made with a Prandtl tube. Entrance conditions to the flume did not appear to have an appreciable affect on the flow behaviour in the flume, and fairly uniform conditions of flow could be attained for a good portion of its length.

2.2 Test Flume, PHOTOGRAPH C-1. The flume was constructed of one-half inch plywood with 2 inch by 4 inch rib joints. The width of



FIGURE· 2.1

OVERALL PLAN OF SPILLWAY MODEL

Scale· 1" = 40'

the flume was 1 foot-3 inches, height 1 foot-6 inches, and length 24 feet. Slope of the flume floor was 1:5.7, and all joints were made water-tight by sealing them with silicone rubber. The test flume itself was centered inside the upstream end of an existing flume, and solid connections to the entrance tank and stilling basin made the slope non-adjustable.

2.3 Entrance Tank, PHOTOGRAPH C-1. This was a rectangular tank, eight feet by six feet, with a height of eight and one-half feet. Water was delivered to this tank through a 12-inch diameter pipe. The tank had a curved approach to the test flume, and in this section was placed a baffle box for the purpose of damping out turbulence and oscillations. This baffle box consisted of a series of vanes (PHOTOGRAPH C-2), which were set at the entrance to the flume.

2.4 Stilling Basin. The stilling basin was attached to the downstream end of the test flume and consisted of a horizontal, rectangular section, one foot-eight inches high, one foot-three inches wide, and eight feet long. An adjustable tail-gate in the stilling basin was used to control flow conditions.

2.5 Datum Levels, PHOTOGRAPH C-3. These consisted of horizontal boards on each side of, and attached to the flume, and set at the same elevation. They served as datums from which velocity and depth readings could be made at any desired point, and were "stepped" in order to keep the vertical distance to the water surface in the flume at a

minimum.

2.6 Prandtl Tube and Manometer. The Prandtl tube was attached to the working portion of a point gauge, and the assembly positioned at a section in the stilling basin four feet from its upstream end. So that any air or debris in the Prandtl tube could be removed, a system was set up whereby the tube and all associated lines could be flushed with water.

2.7 Roughness Elements. TABLES 2.1 and 2.2 show detailed drawings of the roughness elements and spacings used. PHOTOGRAPHS C-2 and C-4 to C-9 show the actual set-up of some of the roughness spacings used. Two shapes of roughness element were used: a standard step shape, e.g. TABLE 2.1, ROW 1, and a backsloped step shape, e.g. TABLE 2.1, ROW 2. There were four separate sizes of standard step shape making up six different arrangements or spacings, TABLES 2.1 and 2.2, ROWS 1, 3, 4, 5, 8, 9, and two separate sizes of backsloped step shape making up four different spacings, TABLES 2.1 and 2.2, ROWS 2, 3, 6, 7, 10. Since the spacing in ROW 3 was a combination of Roughness Spacings 1 and 2, a total of ten roughness element spacings was used for the study. These roughness elements were constructed of one-half inch plywood, and were toe-nailed to the floor of the flume. Silicone rubber was applied to the leading edges to ensure that all of the test discharges passed over the roughness elements.

2.8 PROCEDURE: Initially, discharges up to 2.00 cusecs were run

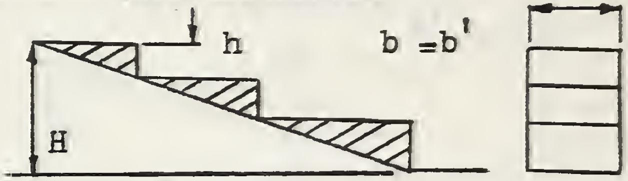
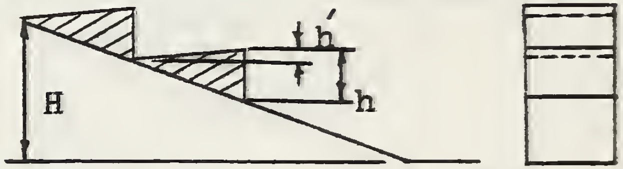
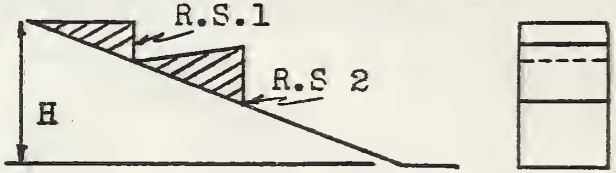
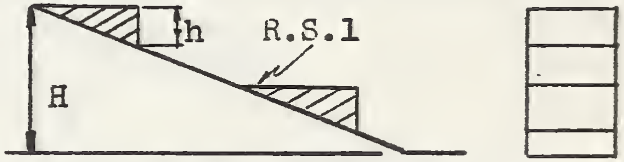
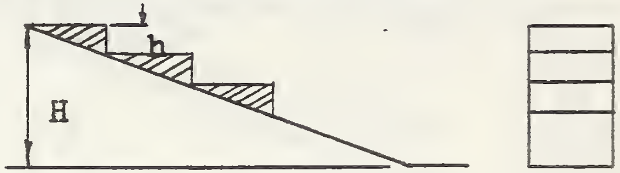
| ROUGHNESS SPACING | DESCRIPTION OF STEPS | H/h | b'/b | NUMBER USED | h'/h | PLAN (Not to Scale) |
|---|---|---|---|---|---|---|
| 1 | TWO-DIMENSIONAL, STANDARD STEP. | 10 | 1 | 10 | 0 |  |
| 2 | TWO-DIMENSIONAL, BACKSLOPED STEP. | 10 | 1 | 10 | 0.374 |  |
| 3 | TWO-DIMENSIONAL, COMBINATION OF 1 AND 2. | - | 1 | 5 R.S.1<br>5 R.S.2 | 0.374 |  |
| 4 | TWO-DIMENSIONAL, STANDARD STEP PLACED ALTERNATELY. | 10 | 1 | 5 | 0 |  |
| 5 | TWO-DIMENSIONAL, STANDARD STEP. | 15 | 1 | 15 | 0 |  |

TABLE 2.1 - ROUGHNESS SPACINGS AND ELEMENTS USED

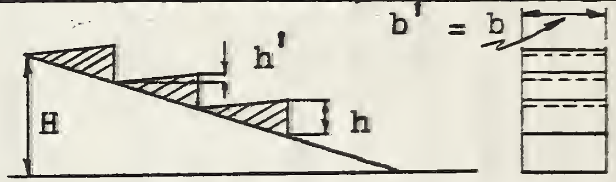
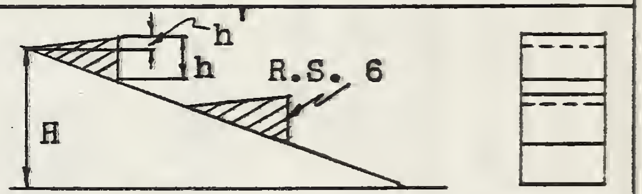
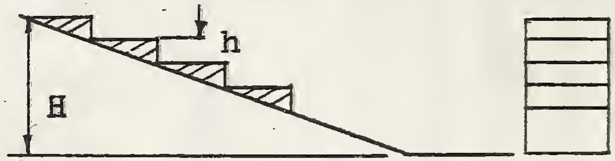
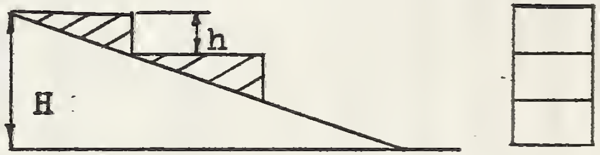
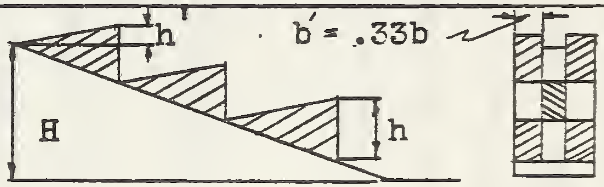
| ROUGHNESS SPACING | DESCRIPTION OF STEPS | H/h | $b'/b$ | NUMBER USED | $h'/h$ | PLAN (Not to Scale) |
|---|---|---|---|---|---|---|
| 6 | TWO-DIMENSIONAL, BACKSLOPED STEP. | 11.42 | 1 | 15 | 0.312 |  |
| 7 | TWO-DIMENSIONAL, BACKSLOPED STEP, ALTERNATELY. | 11.42 | 1 | 8 | 0.312 |  |
| 8 | TWO-DIMENSIONAL, STANDARD STEP. | 20 | 1 | 20 | 0 |  |
| 9 | TWO-DIMENSIONAL, STANDARD STEP. | 7 | 1 | 7 | 0 |  |
| 10 | THREE-DIMENSIONAL, BACKSLOPED STEP, ALTERNATELY | 10 | 0.33 | 15 | 0.374 |  |

TABLE 2.2 - ROUGHNESS SPACINGS AND ELEMENTS USED

through the flume, with no roughness elements placed on the floor of the flume. Following this, roughness elements were used and Roughness Element spacings one to ten were successively installed. For each arrangement of roughness element, a series of discharges was run, up to the maximum possible 2.00 cusecs. In all, a total of 88 runs was made, (See APPENDIX B).

2.9 For each arrangement of roughness elements, the following data were recorded:

(i) Discharge: Initially the calibration tank was used to calibrate the orifice meter. Both devices were used to measure test discharges during the testing period, and if any difference in discharge readings between the two methods was noted, the correct value was assumed to be the one obtained using the weigh tank. Above a test discharge of 1.49 cusecs, only the weigh tank was available to measure test discharges.

(ii) Water Surface Elevation in Entrance Tank: A point gauge located in the entrance tank was set up so that any reading could be interpreted from a graph to give the equivalent elevation of the water surface in the entrance tank, above a chosen datum.

(iii) Velocity Profile: A Prandtl tube was used to obtain a velocity profile at a test section in the stilling basin, which was located about 4 feet downstream from the end of the test flume. Flow conditions here were assumed to be relatively undisturbed

or uniform. The velocity profiles were taken on the centerline of the test section and FIGURE E-1 shows a typical velocity profile.

(iv) Mean Depth: The mean depth of flow was obtained at the point where the velocity profile was taken. Obtaining a depth of flow was difficult because of the up and down movement of the water surface and the turbulent nature of flow. Also entrained air would tend to bulk up the water, so that the depth of flow measured would include an air-water portion. A trial and error method, using the velocity profile, was used to obtain the mean depth and an example calculation is given on PAGE E.2.

(v) Mean Velocity: This value was obtained using the relationship V = q/d, where "q" is the discharge intensity and "d" is the mean depth of flow from (iv). This is assumed to be the mean velocity of flow at the test section where in reality it is the mean velocity of flow only at the point of the section where the velocity profile was taken. It is assumed that the velocity profile at the center of the test section is the same or nearly the same at any point along the test section, i.e. the test conditions are such that a wide channel exists at the test section.

(vi) Water Temperature: Recorded at the start of the day's runs.

(vii) Photographs: These were taken about every second run or where flow conditions showed an interesting behaviour.

(viii) Notes describing the important characteristics of flow were made for each run. These included an estimate of the

maximum height of splash above a roughness elements, an estimate of where approximate uniform conditions of flow were reached on the flume, that is, where terminal conditions of flow behaviour were reached and where or when supercritical and subcritical flow was occuring. An attempt was made to estimate where the possible section of maximum scour potential was located in the stilling basin. Flow leaving the test flume usually entered the stilling basin roughtly in the form of a free overfall or jet. The behaviour of the flow was such that it reached into the stilling basin at various distances,(PARAGRAPH 2.11),so the maximum distance reached by the jet was measured as a possible means of predicting the location of the maximum scour potential. It was assumed that the greatest amount of scour would occur where the jet impinged on the downstream channel. FIGURE D-1 shows where this measurement was taken and is indicated by 1'.

OBSERVATIONS: Observed data are given in TABLES B-1 to B-11.

2.10 Roughness 0: With no roughness elements used, the mean velocity V at the test section varied between 8.25 ft./sec * to 13.00 ft./sec at 0.50 cusecs and 2.00 cusecs respectively. The Froude Number $V/\sqrt{gd}$,varied between 6.55 and 7.45,and these values are an indication of how supercritical the flow at the test section is,where $V/\sqrt{gd} = 1.0$ is taken as the division of supercritical and subcritical flow

2.11 Roughness Spacing 1: The velocity V varied between 4.26 ft./

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* feet per second abbreviated to ft./sec.

sec at 0.56 cusecs to 8.08 ft./sec at 2.00 cusecs, while the Froude Number varied between 2.62 and 3.92, indicating that the roughness elements have caused the resultant flows to be substantially less supercritical than those described in PARAGRAPH 2.10. In general for all discharges used, the flow seemed to accelerate appreciably to the fifth or sixth step from the upstream end, after which the average point of impingement of flow on each step became approximately constant. Close study of the flow showed that on a particular step the portion of flow closest to the walls and floor of the flume did not reach as far downstream as the other portions of flow, probably because of skin friction or drag effects there. Due to these effects, various parts of the flow would reach a following step at different points along this step, which resulted in a mixing or interference action. The intensity of this action increased downstream, until terminal conditions were attained and flow was not accelerating. Also due to this action was the seemingly large increase in air entrainment due to the forced envelopment of air. In a terminal condition, e.g. PHOTOGRAPH C-10, the flow showed a high degree of turbulence with the main portion of flow impinging on every step. This type of flow will be referred to as interference flow.

2.12 The flow on an individual step was mainly supercritical for each of the test discharges run, although at certain times it may have appeared that portions of the flow were above critical depth. This probably occurred because at times the leading edge of the flow was affected less by interference flow and was able to accelerate more

readily and eventually miss a step. Consequently, a portion of the flow on that step would appear deeper than the general depth of flow. It was this height of water which was recorded as the maximum splash height. The maximum splash height measured for Roughness Spacing 1 varied from 0.66 feet at 0.56 cusecs to 1.00 feet at 2.00 cusecs.

2.13 Roughness Spacing 2: The velocity V varied between 1.10 ft./sec. at 0.45 cusecs to 1.43 ft./sec. at 2.00 cusecs, while the Froude Number varied from 0.33 to 2.84. Flow conditions were interesting in that at 0.45 cusecs, a hydraulic jump had formed on every step and in the stilling basin, PHOTOGRAPH C-11. At the next higher test discharge of 0.80 cusecs, all the hydraulic jumps had disappeared and the flow became of the "interference" type. Except for the test discharge of 0.45 cusecs, flow on the steps and in the stilling basin was generally supercritical. Terminal conditions of flow were usually reached on the sixth step, and maximum splash height varied between 0.20 feet at 0.45 cusecs to 1.10 feet at 2.00 cusecs.

2.14 Roughness Spacing 3: PHOTOGRAPH C-12. Velocity V varied between 1.54 ft./sec. at 0.54 cusecs and 7.79 ft./sec. at 2.00 cusecs, while the Froude Number varied between 0.51 and 3.00. At the lower test discharge of 0.54 cusecs, a hydraulic jump occurred on every second step, that is, on every backsloped step, but disappeared at the next highest test discharge of 0.85 cusecs. Terminal conditions of interference flow were usually reached on the sixth step, and maximum splash height varied between 0.60 feet at 0.54 cusecs to 1.30

feet at 2.00 cusecs.

2.15 Roughness Spacing 4: PHOTOGRAPH C-13. The velocity V varied between 5.67 ft./sec at 0.47 cusecs to 9.50 ft./sec at 2.00 cusecs, while the Froude Number varied between 3.86 and 4.16. Interference flow occurred for every discharge and terminal conditions were never attained, as the flow accelerated for the entire length of flume.

2.16 Roughness Spacing 5: PHOTOGRAPH C-14. The velocity V varied between 5.42 ft./sec at 0.45 cusecs to 7.54 ft./sec at 2.00 cusecs, while the Froude Number varied between 2.78 and 3.70. Interference flow occurred for every test discharge, and terminal conditions of interference flow were usually attained by the fifth step. Maximum splash height varied between 0.70 feet at 0.45 cusecs to 1.00 feet at 2.00 cusecs.

2.17 Roughness Spacing 6: PHOTOGRAPH C-15. Velocity V varied between 4.54 ft./sec at 0.59 cusecs to 7.32 ft./sec at 2.00 cusecs, while the Froude Number varied between 2.48 and 2.76. Terminal conditions of interference flow were usually attained on the eighth step. At the test discharge of 0.59 cusecs, a hydraulic jump developed in the stilling basin. Maximum splash height varied between 0.70 feet at 0.59 cusecs to 1.00 feet at 2.00 cusecs.

2.18 Roughness Spacing 7: PHOTOGRAPH C-16. The velocity V varied between 1.24 ft./sec at 0.47 cusecs to 7.43 ft./sec at 2.00 cusecs, while the Froude Number varied between 0.39 and 2.80. A hydraulic jump

developed on every step and in the stilling basin at 0.47 cusecs, while at the next highest test discharge of 0.92 cusecs a hydraulic jump developed on the third step only. Terminal conditions of interference flow were usually attained on the third step, and the maximum splash height varied between 0.60 feet at 0.48 cusecs to 0.80 feet at 2.00 cusecs.

2.19 Roughness Spacing 8: PHOTOGRAPH C-17. The velocity V varied between 1.16 ft./sec. at 0.36 cusecs to 7.85 ft./sec. at 2.00 cusecs, while the Froude Number varied between 0.41 and 3.07. Flow at the higher discharges appeared to skim over the roughness elements, while at the lower test discharge a hydraulic jump developed in the stilling basin. Terminal conditions of interference flow were usually attained on the sixth step, and the maximum splash height was small for all test discharges, remaining at about 0.50 feet.

2.20 Roughness Spacing 9: PHOTOGRAPH C-18. The velocity V varied between 5.59 ft./sec. at 0.63 cusecs to 8.54 ft./sec. at 2.00 cusecs, while the Froude Number varied between 3.27 and 3.50. At test discharges up to about 1.00 cusec, flow appeared to behave as a number of simple overfalls, with a very low intensity of interference flow and little air entrainment. Terminal conditions of interference flow were usually never attained, while maximum splash height varied between 0.40 feet at 0.63 cusecs to 0.90 feet at 2.0 cusecs.

2.21 Roughness Spacing 10: PHOTOGRAPH C-19. The velocity V

varied between 1.43 ft./sec. at 0.50 cusecs to 7.42 ft./sec. at 2.0 cusecs, while the Froude Number varied between 0.48 and 2.80. Referring to the above photograph, it is noted that flow is partially sideways, as some flow falls off laterally from the top of the roughness elements. Splash height was relatively small, and terminal conditions of flow were reached on about the fourth step.

2.22 In PARAGRAPH 2.9.v, it was assumed that a mean velocity obtained from a velocity profile taken at the center of the test section, was the mean velocity of the sectinn. In an attempt to check this assumption, velocity profiles were taken at two other points along the test section to see if they differed greatly. FIGURE 2.2 is a plot of three velocity profiles taken at the ¼ and ½ points of the test section for a test discharge of 2.00 cusecs, when Roughness Spacing 10 was being used. The author considers the flow for this particular set of conditions, to be the most severe test of having uniform flow across the test section. The water leaving the downstream end of the flume had lateral as well as foreward motion , and this effect was transmitted downstream, whereas, this condition was not present when using the other roughness spacings.

2.23 Taking these velocity profiles separately, a mean depth was calculated using the method outlined in APPENDIX E. The value of mean depth ranged from 0.205 feet to 0.218 feet with an average of 0.212 feet. Assuming that this average value is close to the true mean depth,

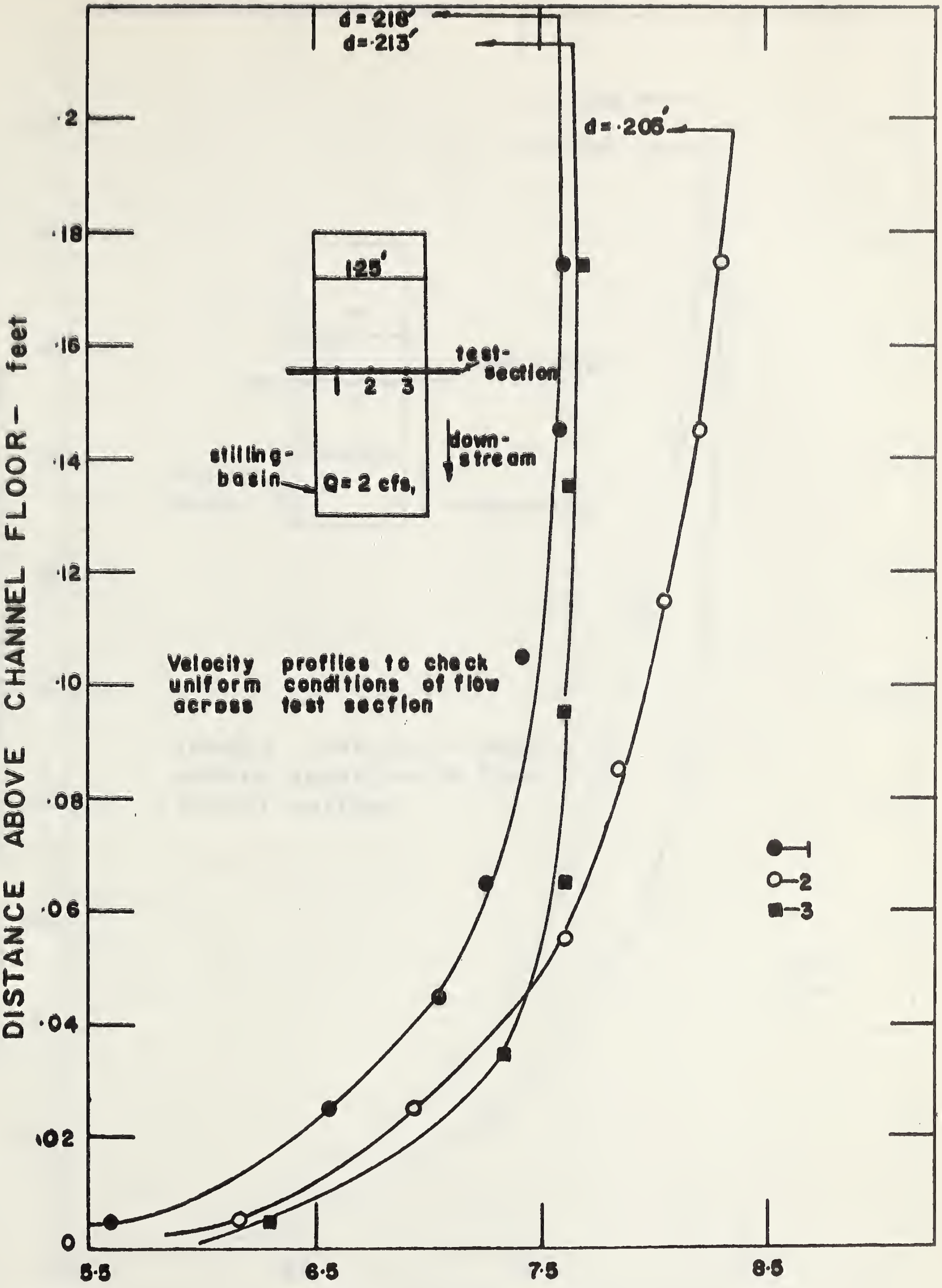

d=·218'
d=·213'
d=·205'
·125'
test-section
1 2 3
down-stream
stilling-basin
Q= 2 cfs,
Velocity profiles to check uniform conditions of flow across test section
DISTANCE ABOVE CHANNEL FLOOR— feet
·2
·18
·16
·14
·12
·10
·08
·06
·04
·02
0
5·5
6·5
7·5
8·5
●—1
○—2
■—3
VELOCITY— feet per second

FIGURE: 2.2

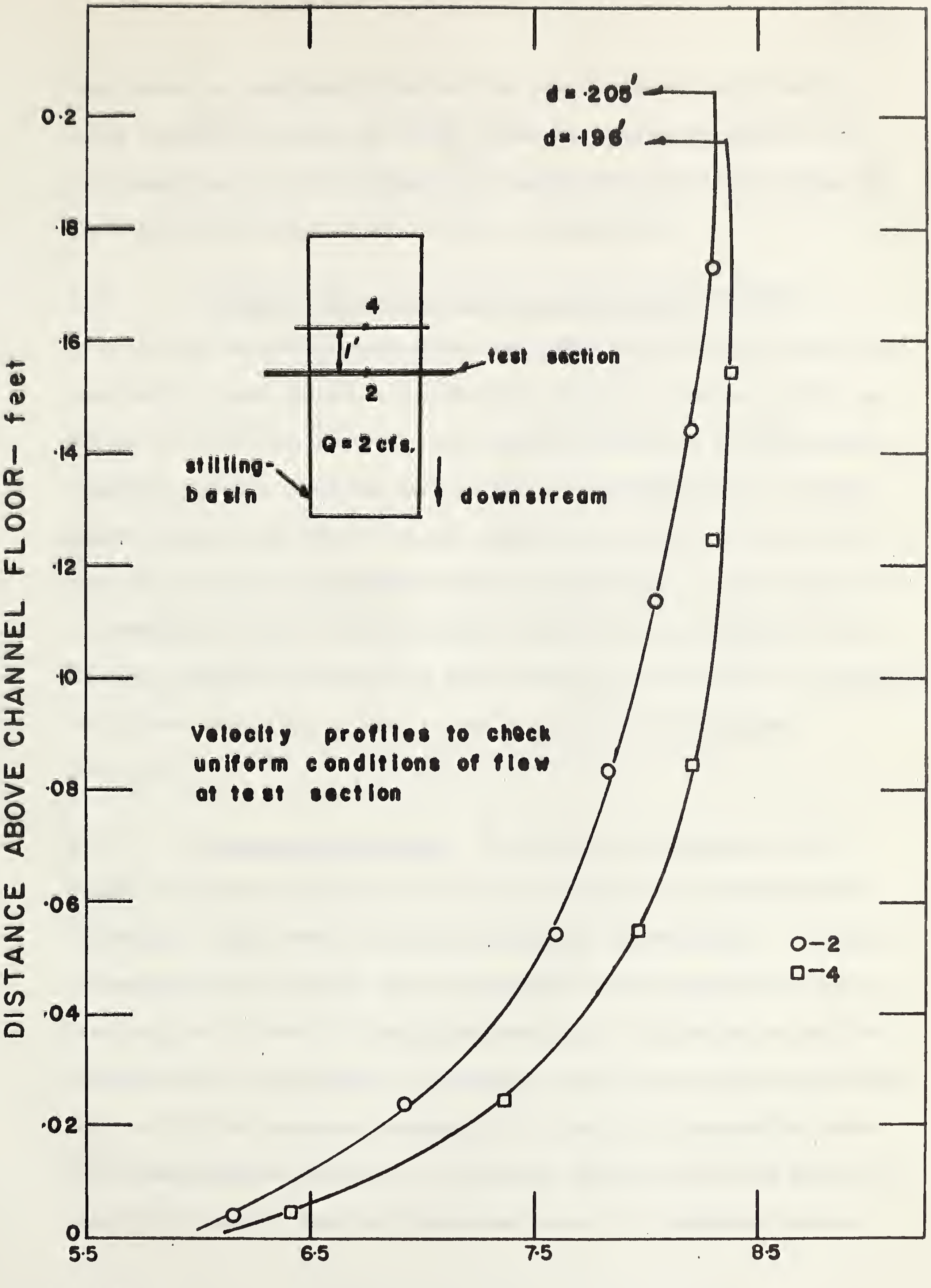

d = ·205′
d = ·196′
4
1′
test section
2
Q = 2 cfs.
stilling-basin
downstream
Velocity profiles to check uniform conditions of flow at test section
○—2
□—4
DISTANCE ABOVE CHANNEL FLOOR— feet
0·2
·18
·16
·14
·12
·10
·08
·06
·04
·02
0
5·5
6·5
7·5
8·5
VELOCITY— feet per second

FIGURE: 2.3

then using the mean depth obtained from the centerline profile only would represent an error of 3.30%. From this, it would appear that the assumption of a wide channel, in finding a mean velocity using the the centerline velocity profile only, is reasonable.

2.24 Uniform Conditions of Flow at Test Section: FIGURE 2.3 is a plot of two velocity profiles, one taken on the center line of the test section, and the other on the center line of a section 1 foot upstream from the test section. The test conditions for discharge and roughness spacing were the same as those in PARAGRAPH 2.22. The mean depths obtained from these velocity profiles were 0.205 feet and 0.196 feet, for the test and upstream sections respectively. This represents a difference of about 3.3%, and since this test was considered to have the most irregular behaviour of flow in the stilling basin, the assumption of uniform conditions of flow at the test section is considered reasonable.

2.25 Maximum Splash Height: The estimates of maximum splash height are given in TABLES B-2 to B-11, in terms of a non-dimensional height $S_m = h_s/d_c$, where $h_s$ was the estimated splash height. Although the measurements of splash may be considered very approximate, they at least may be of value for design purposes where the height of spillway sidewalls must be estimated. In general, the values for $S_m$ varied from 1.10 to 4.50 for Roughness Spacings 1 to 9, while it remained at about 0.75 from Roughness Spacing 10. It must be mentioned that the height of splash was measured from the downstream crest of a roughness element.

It is difficult to generalize design criteria from such data, but the author feels that for the general design case a value of $S_m$=2.25 and $S_m$ = 0.75 for the two-dimensional and three-dimensional roughness elements designs respectively, would provide an adequate sidewall height.

2.26 Air Entrainment: As mentioned previously, the cascade produced in the flume appeared to have a large amount of air entrainment. The author anticipated that air entrainment might create a problem with regard to velocity measurements in the stilling basin, but however; this did not appear to effect the operation of the Prandtl tube to any important degree. Observations of the flow indicated that the entrained air rose to the surface in the form of air bubbles, rapidly enough that flow at the test section was comprised of a small layer of air bubbles clustered on the surface, FIGURE D-1.

2.27 Maximum Scour Potential in Downstream Channel: TABLES B-2 to B-11, COLUMN 13, give the value of 1' in terms of a non-dimensional length 1'/1, where the meaning of 1' was defined in PARAGRAPH 2.9.viii. Because of the idealized conditions of testing in a model and the elimination of many important variables, e.g., an erodible downstream channel would be incorrect to say that the maximum scour in the downstream channel of a prototype spillway structure will occur at a distance 1'. However, scour would probably begin in the immediate vicinity where the flow impinges on the downstream channel, so that an estimate of this length would give some idea where this area might be. From this point

of view the following table is given for reference.

## TABLE 2.3

## ESTIMATING WHERE FLOW FROM CHUTE IMPINGES ON DOWNSTREAM CHANNEL

| ROUGHNESS SPACING | 1'/1 (AVE. EXP. VALUES) |
|---|---|
| 1 | 0.62 |
| 2 | 0.85 |
| 3 | 0.74 |
| 4 | 1.00 |
| 5 | 0.62 |
| 6 | 0.60 |
| 7 | 0.55 |
| 8 | - * |
| 9 | 0.45 |
| 10 | 1.00 |

* - Difficult to estimate where flow impinges in stilling basin.

# CHAPTER III

## ANALYSIS OF EXPERIMENTAL DATA

3.1 The flow over the roughness elements was very turbulent, so to define the flow there was not practical. Flow in the stilling basin, and upstream of the steps, did allow measurements. As theoretical calculation of energy losses was impractical, the measureable data were related with the aid of dimensional analysis.

3.2 DIMENSIONAL ANALYSIS: The behaviour of the flow can be specified as follows; suppose a discharge intensity q is applied to a long-crested weir, followed by a chute of slope S and breadth b, fitted with roughness elements of non-dimensional size e and shape and pattern represented by non-dimensional factors $\alpha$. The fluid has dynamic viscosity $\mu$ and mass density $\rho$, and the flow takes place under a gravitational body force g. The roughness of the material of the steps is assumed unimportant. Then flow down the slope is determined at every point P, distant $H_T$ vertically below the upstream total head line. Thus, if $H_L$ is the head lost due to the roughness elements from the weir crest down to the point P, and if (for convenience) we imagine that, at the point P, a horizontal floor is inserted and the depth at which flow first becomes undisturbed there is d, then:

$$H_L,\ d = \text{fns.}\ (q,\ S,\ b,\ e,\ \alpha\ \ldots\ldots\ldots\ldots\ldots\ldots,\ \rho,\ \mu,\ g, H_T)\ldots(3.2.1)$$

Rearranging the variables in this equation, then:

$$\frac{H_L}{\sqrt[3]{q^2/g}} = \text{fns.}\left(\frac{H_L}{H_T},\ \frac{q}{\nu},\ \frac{b}{\sqrt[3]{q^2/g}},\ e,\ \alpha,\ S\right)\ \ldots\ldots\ldots\ldots\ldots\ldots(3.2.2)$$

where $d_c = \sqrt[3]{q^2/g}$

$$\frac{d}{H_T} = \text{fns.}\ \left(\frac{d_c}{H_T},\ \frac{q}{\nu},\ \frac{b}{\sqrt[3]{q^2/g}},\ e, \alpha,\ S\right)\ \ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.2.3)$$

3.3 In open channel flow, the state of flow is governed basically by the effects of viscosity and gravity relative to the inertial forces of flow. Now $q/\nu$ , is the Reynolds' Number, and is a measure of the effects of viscosity relative to those of inertia. Structures such as spillways and stilling pools have inertial forces that are much greater than viscous and turbulent shear forces, so that the term $q/\nu$ does not matter. The term $b/d_c$ seems likely to matter over some range, but we hope it will not be too important here. The value of $b/d_c$ in this study varies between 3.5 and 6.0, which for the purpose of analyzing experimental data may be assumed essentially constant. The terms e and $\alpha$ are fixed for any one roughness element design and S may be important over some range but is constant in this study.

3.4 Considering EQUATION 3.2.2, if $H_T$ = fn. ($H_L$), then the analysis justified plotting $d_c/H_T$ against the percentage loss of head $H_L/H_T$, down the slope. As a refinement the "friction loss" due to the material of the steps alone might be estimated,

necessarily roughly, and deducted from the total loss to give the "roughness element loss", but this seems unjustified initially. Deviations of points from the fitting line for one design might be checked for the effect of $b/d_c$, but the amount of data required to show a clear effect is likely unobtainable in this preliminary investigation. The factors $\alpha$ , defining the shape and pattern of roughness elements in the flume cannot be measured readily, so merely draw attention to a possible need for comparing plotted points for separate shapes and arrangements of steps.

3.5 "Efficiency of Energy Dissipation" ($\eta_f$), will be defined as the ratio of the energy loss of flow in passing through the flume to the test section, $H_L$, to the total upstream head, $H_T$, expressed as a percentage. A combined plot of $d_c/H_T$ vs. $\eta_f$ is given in FIGURE 3.1, data for which are recorded in TABLES B-1 to B-11, COLUMNS 9 and 10. Because the normal procedure in the design of a spillway is to develop a hydraulic jump in a stilling basin, an "equivalent hydraulic jump efficiency curve", has been drawn on FIGURE 3.1. The data for this curve were obtained by calculating the sequent depth of a hydraulic jump, from the mean depths of flow for Roughness 0, TABLE B-1, COLUMN 4, and finding the new efficiency of energy dissipation. This allows a comparison between energy dissipated by a cascade only and a system where the energy dissipated depends mainly on a hydraulic jump developed in a stilling basin. Thus cascade designs plotting to the right of this

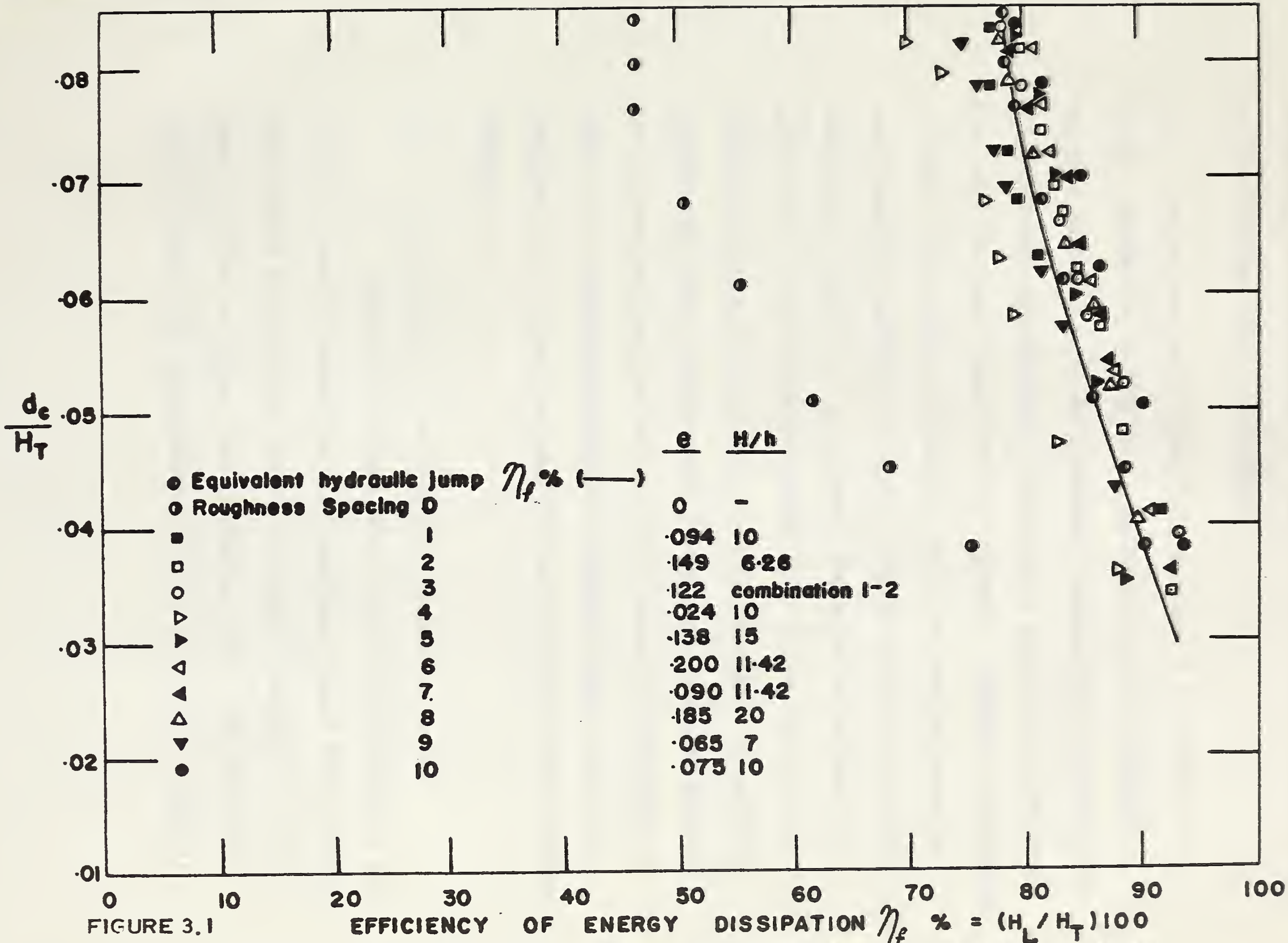


FIGURE 3.1

RATIO OF CRITICAL DEPTH OF FLOW TO TOTAL HEAD VS· EFFICIENCY OF ENERGY DISSIPATION

curve would be dissipating more energy than a single hydraulic jump in the stilling basin of the model.

3.6 Before analyzing FIGURE 3.1, the term e is defined as $A_e/L_T^2$ , APPENDIX D, FIGURE D-2. The value of e is considered a function of the size of the roughness elements only when the overall roughness conformation of the flume is gemetrically the same, i.e. when the shape factors $\alpha$ are constant. Therefore considering a "step" design where a continuous series of standard steps are used (Roughness Spacings 1,5,8,9), a higher value of e will mean a smaller step height h or a greater number of steps used for a given drop H, e.g. Roughness Spacing 1,e = 0.094, H/h = 10 and Roughness Spacing 8,e = 0.185, H/h = 20. Therefore in comparing experimental data, reference will be made to e values with the idea of comparing step size for a given shape and arrangement of step, e.g. a continuous series of backsloped steps, (Roughness Spacings 2, 6), or an alternated series of standard steps,(Roughness Spacing 4 ).

3.7 From FIGURE 3.1, the following points are noted:

(i) Comparison of the plotted points for Roughness 0 and for those where a cascade has been developed, shows that a cascade considerably increases the amount of energy dissipated on a chute, especially for the higher test discharges used. For values of $d_c/H_T$ of about 0.08, approximately 46% of the initial energy is

dissipated when no roughness elements are used, while for the same range of discharge, cascades dissipated approximately 80% of the initial energy.

(ii) There is a decrease in efficiency of energy dissipation with an increase in discharge for each of the roughness spacings used, but the efficiency seems to tend to a limit of about 80%.

(iii) Data for Roughness Spacings 1,4 and 9 plot to the left of the "equivalent hydraulic jump efficiency curve", while the remainder plot to the right of it.

(iv) For the "standard step shape" of roughness element (Roughness Spacings 1,4,5,8,9), the performance of a cascade developed by a continuous series of standard steps, in increasing order of overall efficiency, is 9,1,5 and 8 respectively, below a value of $d_c/H_T$ of about 0.065; i.e. the data for the above roughness designs plot successively to the right of each other. Above this value there is a comparable decrease in energy dissipating efficiency between Roughness Spacings 5 and 8, so that the position of data in increasing order of efficiency is now 9,1,8 and 5. Thus it would seem there is a limiting value of step size given by H/h or e, between 15 and 20, or 0.138 and 0.185 respectively, above a value of $d_c/H_T$ of 0.065, which would develop the most efficient

cascade for dissipating energy. Below this value of $d_c/H_T$, the limiting step size or the best step size appears to be about H/h =20.

(v) For the backsloped step shape of roughness element (Roughness Spacings 2,6,7), the overall efficiency is greater for Roughness Spacing 6 than for Roughness Spacing 2, in designs comprised of a continuous series of backsloped steps. This again indicates there will be an increase in the energy dissipation, with an increase in the number of steps used, but what the limiting or most desirable number to use is, cannot be predicted from the data available. The value of backsloping a step of given length "l" is noted, when comparing the position of the plotted points for Roughness Spacings 1 and 2. The step length of these two roughness designs is the same, but those of Roughness Spacing 2 have been backsloped, with the result that the overall efficiency of the resulting cascade has been increased. This point is also evident in comparing the position of data for Roughness Spacings 5 and 6. Another interesting point is that the cascade produced by Roughness Spacing 7, dissipated about the same amount of energy as that for Roughness Spacing 6, even though the steps were alternated for the first step design. This is in sharp contrast to the performance of Roughness Spacings 1 and 4 where alternating a series of standard steps in the latter design, greatly reduced the overall efficiency of energy dissipation from that of Roughness Spacing 1.

(vi) Roughness Spacing 10 provided the best overall efficiency of energy dissipation. This may possibly be attributed to the type of flow created by these three-dimensional roughness elements. For the two-dimensional roughness elements the flow was of the interference type, having a direction of flow mainly downstream, whereas for Roughness Spacing 10, flow was partly lateral, thus causing a different form of interference action than that described in PARAGRAPH 2.11. PHOTOGRAPH C-19 shows that parts of the flow seemingly meander down the flume as water flows off the tops of the roughness elements in a sideways direction, causing a large interference of movement where flow is moving laterally.

3.8 Considering EQUATION 3.2.3, the analysis justifies using experimental data in another way, by plotting $H_T/d$ against $d_c/H_T$. The terms $q/\nu$ , $b/d_c$ and S are not considered in the analysis, for reasons stated in PARAGRAPH 3.3, and data are plotted on separate graphs for separate shapes and arrangements of roughness elements. Also since $H_T$ appears in both of the above parameters, then a plot of d against $d_c$ might show a good correlation.

3.9 Attempts at finding the amount of correlation between the above variables using experimental data have been made as follows:

(i) FIGURE 3.2 and FIGURE 3.5, are plots of $H_T/d$ against $d_c/H_T$, and d against $d_c$, respectively, for the two-dimensional

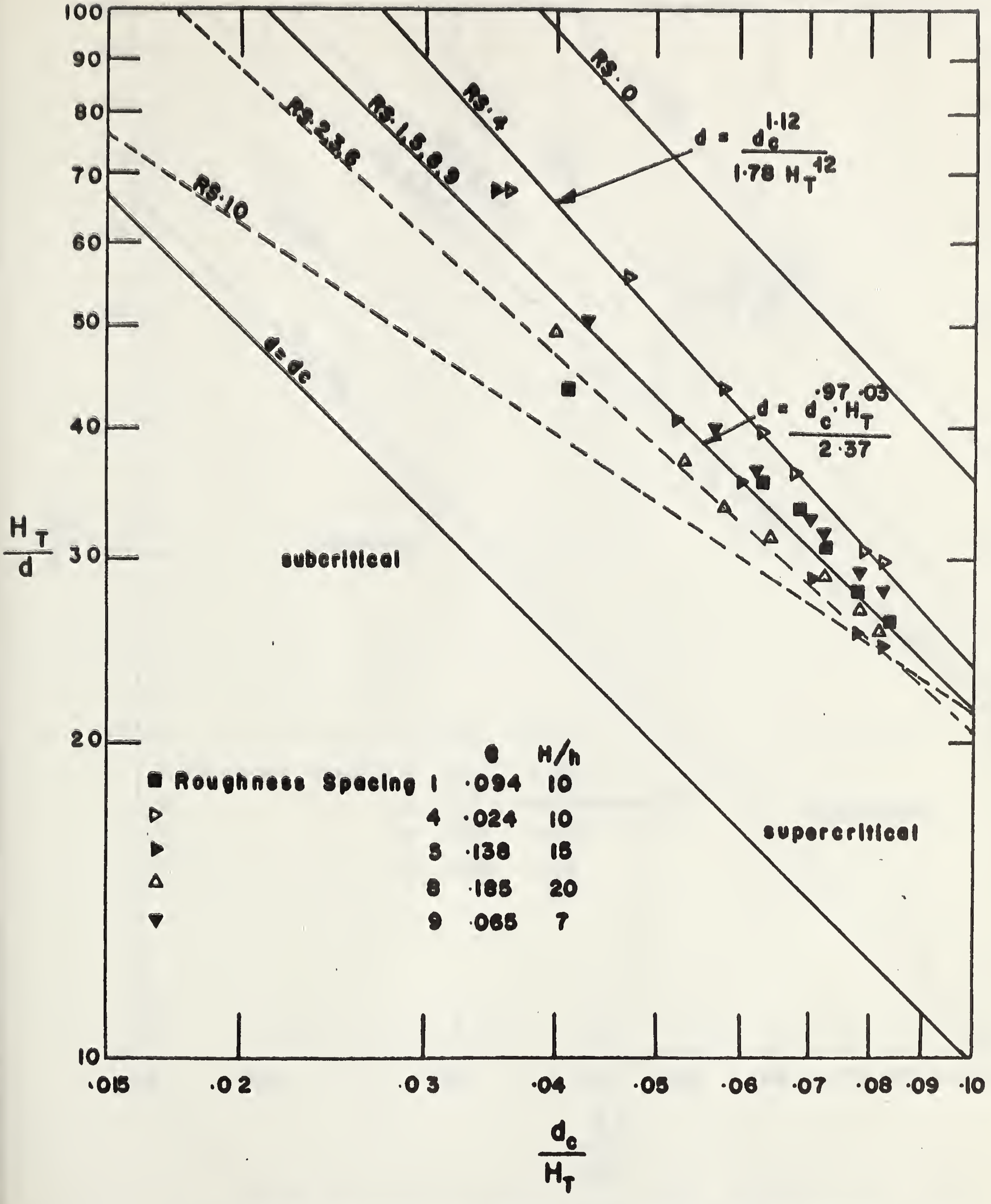


FIGURE 3.2 RATIO OF TOTAL HEAD TO MEAN DEPTH OF FLOW
VS.
RATIO OF CRITICAL DEPTH OF FLOW TO TOTAL HEAD

[illegible]

[illegible]

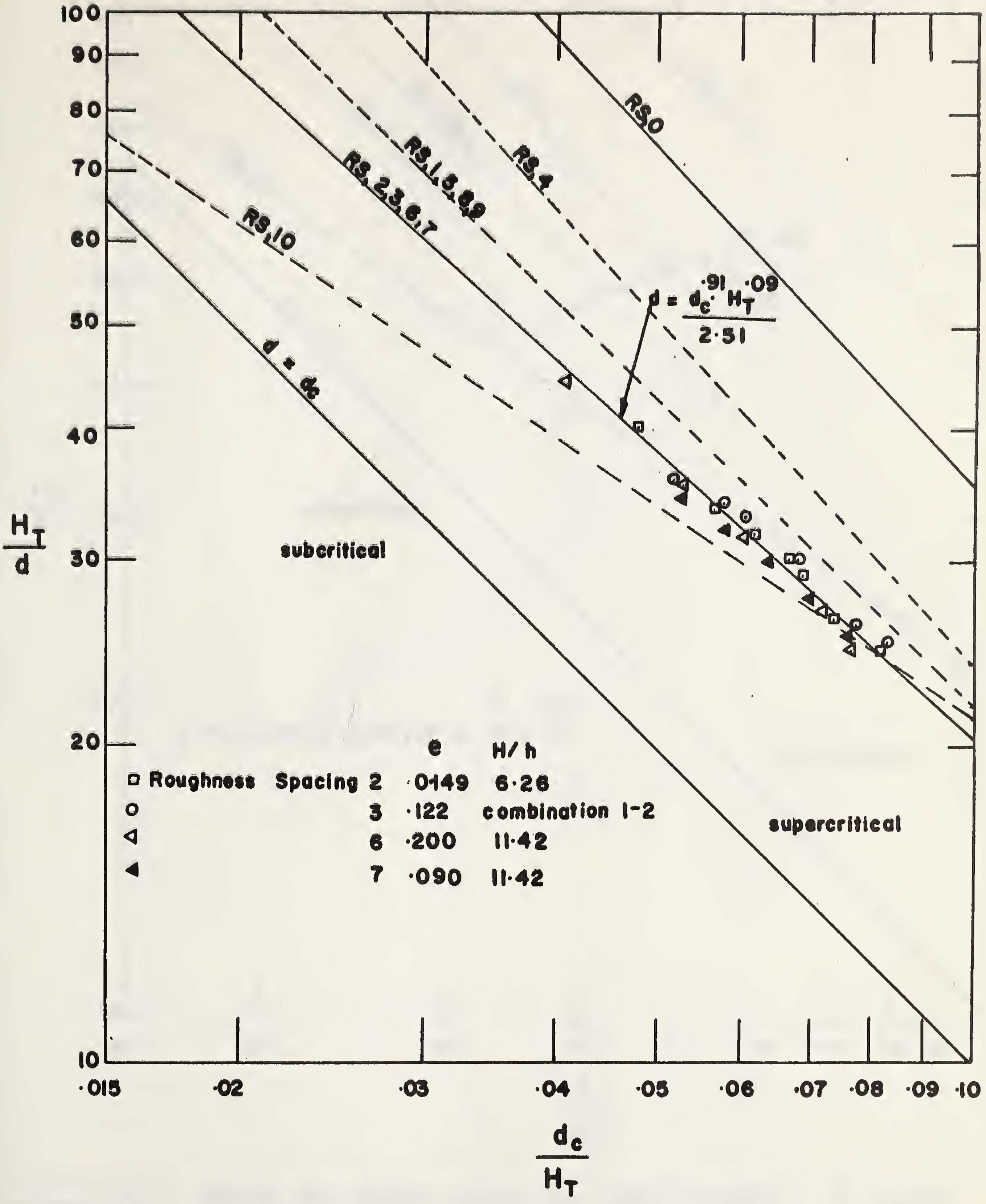


FIGURE: 3.3 RATIO OF TOTAL HEAD TO MEAN DEPTH OF FLOW VS. RATIO OF CRITICAL DEPTH OF FLOW TO TOTAL HEAD

[illegible]

[illegible]

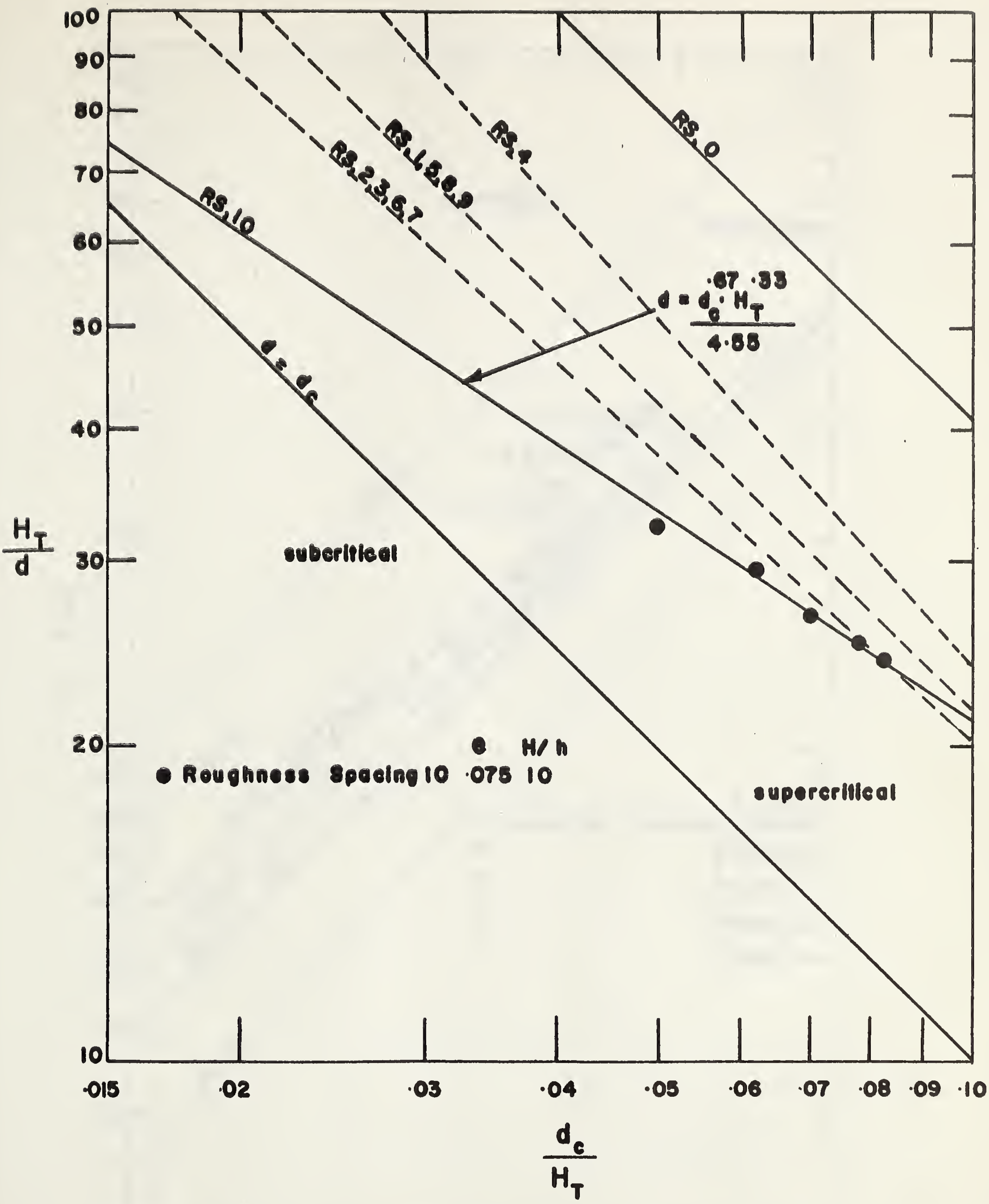
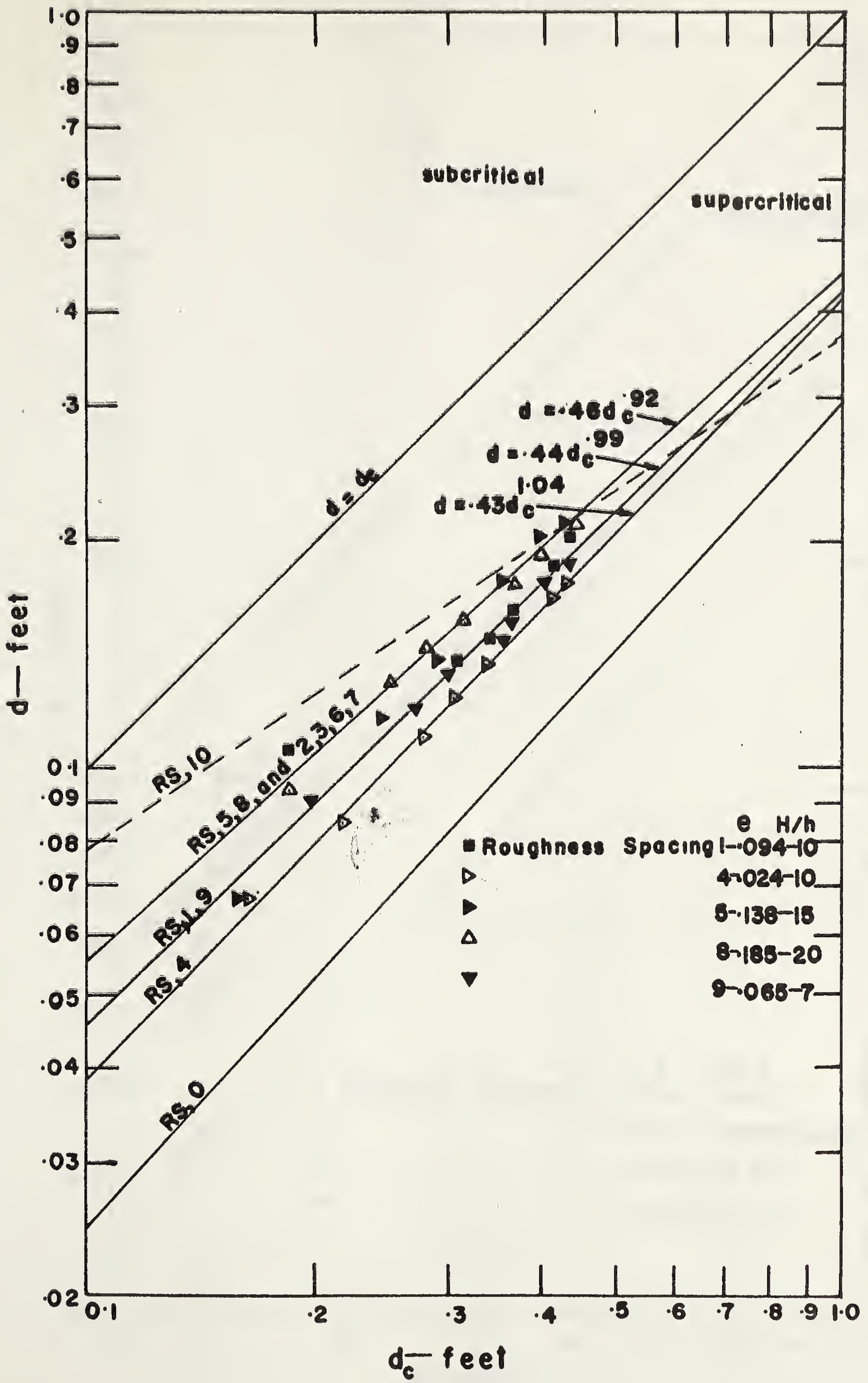


FIGURE: 3.4 RATIO OF TOTAL HEAD TO MEAN DEPTH OF FLOW VS. RATIO OF CRITICAL DEPTH OF FLOW TO TOTAL HEAD

[illegible]

[illegible]



FIG·3.5 MEAN DEPTH VS· CRITICAL DEPTH OF FLOW

[illegible]

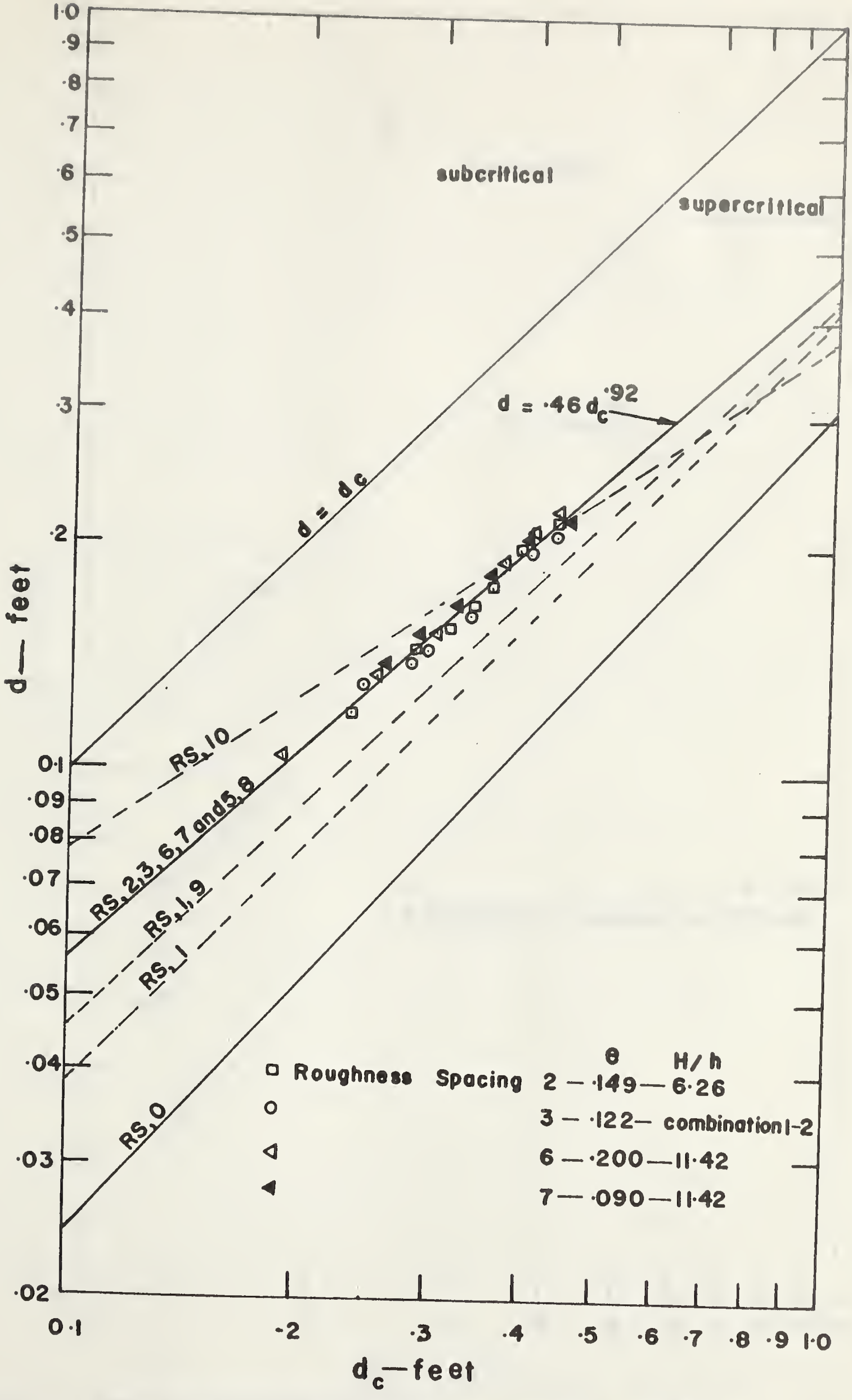


FIG. 3.6 MEAN DEPTH VS. CRITICAL DEPTH OF FLOW

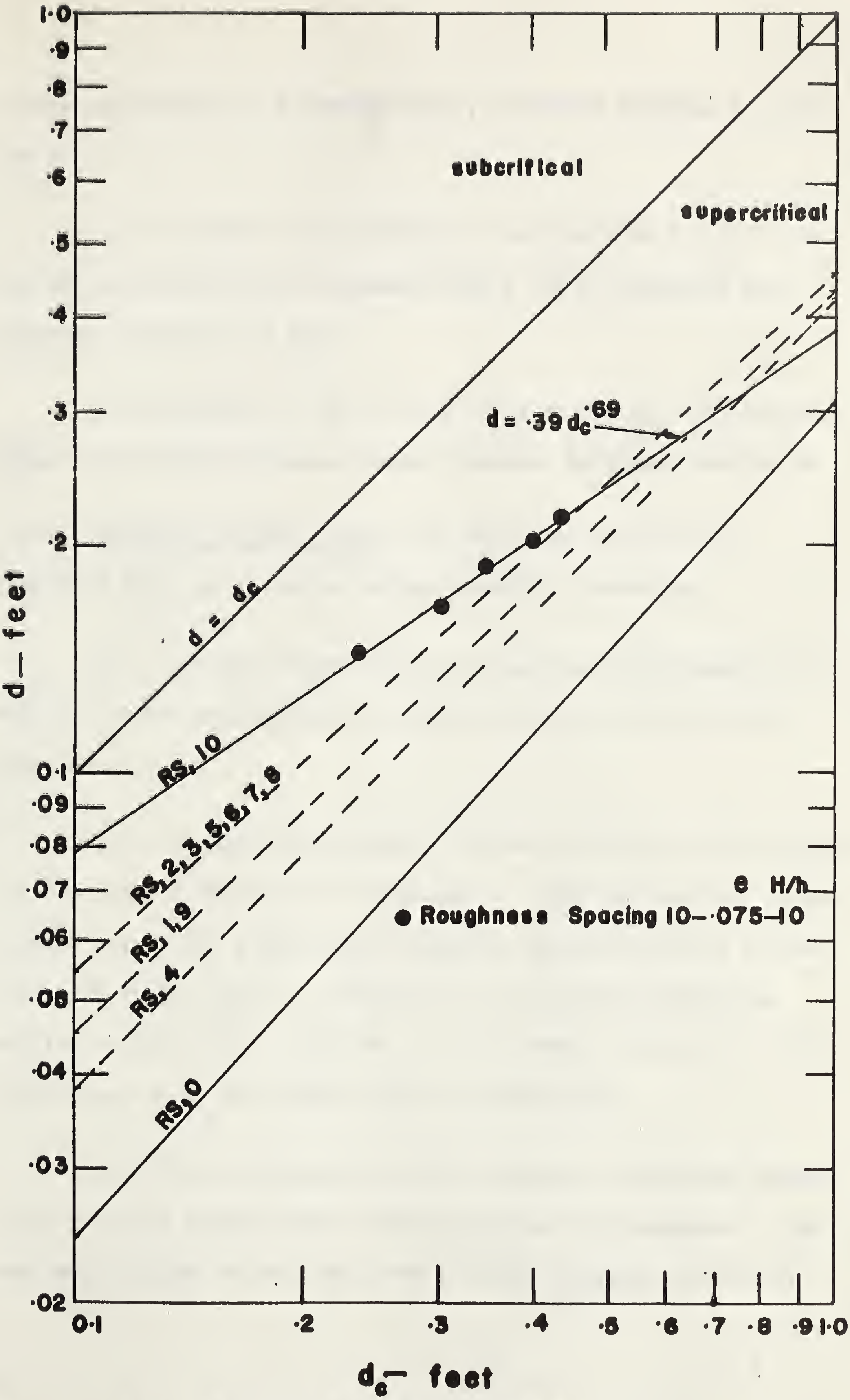


FIG. 3.7 MEAN DEPTH VS. CRITICAL DEPTH OF FLOW

roughness elements of a standard step, Roughness Spacings 1,4,5,8, and 9.

(ii) FIGURE 3.3 and FIGURE 3.6 are plots as for (i), but for the two-dimensional roughness element of a backsloped step, Roughness Spacings 2,6 and 7.

(iii) FIGURE 3.4 and 3.7 are plots as for (i), but for the three-dimensional roughness element design, Roughness Spacing 10.

3.10 Analysis of These Plots: In analyzing the plots of PARAGRAPH 3.9, the following points should be considered.

(i) On each of the graphs is the line which separates the subcritical and supercritical regimes of flow, ie. for the case where $d = d_c$.

(ii) On each of the graphs has been drawn the line locating the position of the data for Roughness 0. Thus the position of the plotted points for a particular roughness spacing relative to the above two lines, gives an indication of the energy dissipating ability of the cascade produced, i.e. the nearer the plots to the subcritical zone, the better is the cascade design.

(iii) For a particular graph, lines have been drawn through sets of points showing their average position and alignment. This was done in order to note any trends in the alignment of sets of

data between various roughness spacings, and to obtain some equations for design purposes.

(iv) For a particular graph, lines drawn as in (iii) are shown as dashed lines for comparative purposes.

## Plots of $H_T/d$ Against $d_c/H_T$

3.11 FIGURE 3.2 shows that a cascade will dissipate a substantial amount of energy of flow, since data for cascade designs plot much closer to the critical line than does data for Roughness 0. When considering a continuous series of standard steps, Roughness Spacings 1,5,8 and 9, it is noted that there is a progression of sets of data towards the critical line when the number of steps used is increased. At about $d_c/H_T = 0.065$, the alignment of the data for Roughness Spacings 5 and 8 cross, indicating that above this value of $d_c/H_T$, 15 steps will produce a more efficient cascade than will 20 steps. The existance of a limiting or most desirable number of steps was mentioned in PARAGRAPH 3.7.iv. Thus increasing the number of steps above 20 may have increased the energy dissipated for a value of $d_c/H_T < 0.065$, but the limiting number when $d_c/H_T$ becomes unimportant, would be impossible to predict from available data. Roughness Spacing 4 produced the least efficient cascade of any roughness design, as is evidenced by the proximity of its data to the Roughness 0 line.

3.12 FIGURE 3.3 points out the value of backsloping a step. Relatively, data for the backsloped step designs are located closer to the subcritical zone than data for the standard step designs. This is particularly noticeable when comparing the location of data for Roughness Spacings 1 and 2 or 5 and 6, where data for Roughness Spacing 2 are located closer to the subcritical zone than are data for Roughness Spacing 1, and similarily Roughness Spacing 6 data are closer to the subcritical zone than Roughness Spacing 5 data.

3.13 FIGURE 3.4 indicates that from the proximity of data for Roughness Spacing 10 to the critical line, this design provided the best cascade for dissipating energy. However, an interesting point to note is that the data plot at a flatter slope than those for the two-dimensional roughness element designs. Possibly this may be attributed to the presence of a space between roughness elements which permits flow to accelerate in this area, so that the lateral direction of flow apparently so important in causing an interference action (PARAGRAPH 3.7. vi), must greatly decrease with increasing discharge.

3.14 Plots of d against $d_c$: The purpose of these plots was merely to ascertain the extent of the relationship $d = fn(d_c)$, (PARAGRAPH 3.8). The relative position of data plotted (FIGURES 3.5 to 3.7), with respect to the Roughness 0 line and critical line, are as explained in PARAGRAPH 3.11 to 3.13. For reference, the equations describing the approximate behaviour of data

are given on these figures.

3.15 For a cascade developed in a spillway chute by roughness elements of the type specified, the flow in the downstream channel where it is relatively undisturbed, may be estimated using the following equations:

(i) Continuous series of standard steps, best design is $H/h = 20$ when $d_c/H_T$ is less than 0.065, and $H/h = 15$ when $d_c/H_T$ is greater than 0.065.

$$d = \frac{d_c^{0.91} \cdot H_T^{0.09}}{2.51} \quad \text{..................} (3.15.1)$$

(ii) Continuous series of backsloped steps - 15 steps in a given drop H, where $H/h = 11.42$, produced the best energy dissipation. Design equation is 3.15.1

(iii) Three-dimensional roughness elements, for a design with roughness elements of the same relative size in the prototype as for Roughness Spacing 10.

$$d = \frac{d_c^{0.67} \cdot H_T^{0.33}}{4.55} \quad \text{..................} (3.15.2)$$

# CHAPTER IV

## CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions: A model study investigating the use of cascades for dissipating energy of flow has shown that:

(i) A well designed cascade can dissipate a substantial percentage of energy before flow reaches the downstream channel.

(ii) For a continuous series of standard steps, there appears to be a limiting size of step, "h", which for a given total drop H will produce the best cascade for dissipating energy. Experimental data indicates that this limiting size is about H/h = 20 when $d_c/H_T$ is less than 0.065, and about H/h = 15 when $d_c/H_T$ is greater than 0.065, (FIGURES 3.1 and 3.2).

(iii) Backsloping a step of given length 1 increases the energy dissipated by a cascade, (PARAGRAPH 3.7.iv).

(iv) For a given shape and arrangement of roughness elements, the flow in the downstream channel where it is fairly undisturbed may be described approximately by an equation of the form $d = \frac{d_c^m \cdot H_T^n}{C}$, where m, n, and C are constants depending on test conditions, (FIGURES 3.2, 3.3, 3.4).

(v) Use of a series of three-dimensional steps offered the most desirable cascade for energy dissipation, (PARAGRAPH 3.7.vi).

4.2 Recommendations: Further study of the ability of cascades to dissipate energy of flow, is recommended on the following:

(i) Effect on the energy dissipation of a cascade, when the slope of the flume is varied in the range of 1 vertical:1 horizontal to 1 vertical:10 horizontal.

(ii) Expansion on the use of three-dimensional roughness elements, since these provided the best cascade design in this study.

(iii) Effect of using devices such as vanes or baffles on the first upstream step, in order to decrease time required for flow on chute to reach terminal conditions. Observations (TABLES 3.2 to 3.11), indicate that up to one-half the length of chute was required for the cascade to reach terminal conditions flow. It is possible that these devices on the first step could have caused terminal conditions of interference flow to be attained sooner, thus increasing the energy dissipation.

# CHAPTER V

## PRACTICAL APPLICATIONS OF CASCADES

5.1 The non-dimensional plots of FIGURES 3.2 to 3.4 offer a possible means of applying the model results to a prototype structure. PARAGRAPH 3.15 outlines the shapes and sizes of steps which developed the best cascades for dissipating energy, and if these are proportionately the same size in some prototype, it is assumed that flow conditions at the base of the chute can be defined approximately by EQUATION 3.15.1 or 3.15.2. Considering the Froude Number $V/\sqrt{gd}$, TABLES B-2 to B-11, COLUMN 6, it appears that the flow leaving a spillway chute on which a cascade has been developed, would be supercritical. Because a substantial percentage of energy will have been dissipated on the chute, the author believes that the use of a cascade, along with a hydraulic jump at the base of the chute, would be practical. The use of a cascade makes the jump equivalent to that from a smaller drop without a cascade, thus allowing a reduction in the size of the stilling basin.

5.2 The effect of varying the slope of the model on the energy dissipation by a cascade, was not a part of this study. It seems probable that as the slope of the chute is increased, flow would have a tendency to skip steps, which would result in a decrease in the

energy dissipated by the cascade. Indications are that for steep slopes such as 1:1, flow tends to skip steps e.g. Gilboa Dam (Gausmann and Madden, 1923), while for a flatter slope of 1:2, a cascade design using about the same shape and number of steps as for the Gilboa Dam (Heinly, 1915), was satisfactory. From these the author feels that the results of this study could be applied to prototype structures having a slope of up to about 1:1.5, and design discharges of up to about 80 cusecs per foot.

5.3 In order to illustrate the practical application of the reresults from this study, an example design is given on PAGE E-5.

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# APPENDIX A

# APPENDIX A

## GLOSSARY OF TERMS

| | |
|---|---|
| $b$ | Breadth of flume,in feet. |
| $b'$ | Breadth of a roughness element, in feet. |
| $d$ | Mean depth of flow as measured at test sectinn,in feet. |
| $d_c$ | Critical depth of flow for a given test discharge intensity, in feet. |
| $d_T$ | Sequent depth of a hydraulic jump, in a stilling basin having no chute blocks or end sill, in feet. |
| $e$ | A measure of the size of roughness in the flume for a given shape and arrangement of roughness element, where $e = A_e/l_T^2$. |
| $g$ | Acceleration due to gravity, ft./sec.$^2$. |
| $h$ | Vertical height of a roughness element at its downstream end, in feet. |
| $h'$ | The vertical distance which a roughness element has been backsloped, in feet. |
| $h_N$ | Perpendicular distance from the floor of the flume to the downstream crest of a roughness element, in feet. |
| $l$ | Horizontal length of a roughness element, in feet. |
| $l'$ | An estimated distance from where the flow leaves the downstream end of the flume to where it impinges on the stilling basin, in feet. |
| $l_T$ | The horizontal distance between the toe of one roughness |

| | |
|---|---|
| | element and the toe of the succeding one downstream, in feet. |
| $q$ | Discharge intensity in cubic feet per second per foot. |
| $A_e$ | Maximum area of a roughness element which is perpendicular to the slope of the flume, in feet. |
| $E_f$ | Specific energy of flow at the test section in the stilling basin, in feet. |
| $F$ | Froude No. of flow at the test section where $F=V/\sqrt{gd}$. |
| $H$ | Difference in elevation between the upstream crest of the flume and the floor of the stilling basin at the test section, in feet. |
| $H_L$ | Energy loss through flume,in feet. |
| $H_T$ | Total head upstream of steps measured from the floor of the stilling basin at the test section, in feet. |
| $S$ | Slope of the flume. |
| $h_s$ | Maximum splash height measured from the crest of a step, in feet. |
| $S_m$ | A non-dimensional number expressing the maximum splash height ($h_s$) in terms of the critical depth of flow,$(h_s/d_c)$ |
| $V$ | Mean velocity of flow at the test section, in feet per second. |
| $V_c$ | Critical velocity of flow in feet per second. |
| $V_T$ | Mean velocity of flow immediately downstream of hydraulic jump, in feet per second. |
| $\alpha$ | Shape factors, that define form and arrangement of |

| | |
|---|---|
| | steps, non-dimensional. |
| $\nu$ | Kinematic viscosity, in feet$^2$ per second. |
| $\rho$ | Mass density, in slugs per foot$^3$. |
| $\eta_f$ | Efficiency of energy dissipation, %. |

# APPENDIX B

## TABLE B-1

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ - | (11) $H_T/d$ - | (12) $S_m$ - | (13) 1'/1 - | (14) TERMINAL FLOW -STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROUGHNESS SPACING 0; e - 0; H/h = - | | | | | | | | | | | | | |
| 37 | .50 | 8.25 | .049 | .171 | 6.55 | 4.49 | 1.11 | 75.4 | .038 | 91.7 | - | - | - |
| 38 | 2.00 | 13.10 | .124 | .430 | 6.55 | 5.20 | 2.79 | 46.2 | .084 | 41.8 | - | - | - |
| 40 | 1.09 | 11.54 | .077 | .291 | 7.35 | 4.80 | 2.15 | 55.4 | .061 | 62.4 | - | - | - |
| 43 | 1.36 | 12.25 | .088 | .332 | 7.30 | 4.91 | 2.43 | 50.6 | .068 | 55.9 | - | - | - |
| 44 | .64 | 9.50 | .054 | .204 | 7.20 | 4.57 | 1.45 | 68.2 | .045 | 84.0 | - | - | - |
| 45 | 1.69 | 12.95 | .104 | .384 | 7.10 | 5.05 | 2.72 | 46.2 | .076 | 48.5 | - | - | - |
| 46 | .83 | 10.54 | .063 | .239 | 7.45 | 4.67 | 1.79 | 61.7 | .057 | 74.1 | - | - | - |
| 47 | 1.86 | 13.10 | .114 | .410 | 6.80 | 5.12 | 2.78 | 45.5 | .080 | 45.1 | - | - | - |

## TABLE B-2

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ - | (11) $H_T/d$ - | (12) $S_m$ - | (13) 1'/1 - | (14) TERMINAL FLOW STEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROUGHNESS SPACING 1; e - 0.094; H/h = 10 | | | | | | | | | | | | | |
| 1 | .561 | 4.26 | .105 | .185 | 2.32 | 4.58 | .39 | 91.6 | .041 | 43.5 | 3.6 | .34 | 5 |
| 3 | 1.22 | 7.07 | .138 | .309 | 3.37 | 4.91 | .92 | 81.4 | .063 | 35.6 | 2.9 | .60 | 6 |
| 9 | 1.87 | 8.08 | .185 | .412 | 3.31 | 5.19 | 1.20 | 77.1 | .078 | 28.0 | 2.3 | .62 | 6 |
| 26 | 2.00 | 8.04 | .201 | .434 | 3.16 | 5.25 | 1.20 | 77.1 | .083 | 26.1 | 2.3 | .64 | 6 |
| 27 | 1.39 | 7.55 | .148 | .338 | 3.47 | 4.98 | 1.04 | 79.2 | .068 | 33.6 | 2.3 | - | 6 |
| 29 | 1.56 | 7.65 | .163 | .363 | 3.34 | 5.06 | 1.07 | 78.8 | .072 | 31.0 | 2.3 | - | 6 |

(14) Step where terminal conditions of flow reached

| (1)<br>RUN | (2)<br>Q<br>cusecs | (3)<br>V<br>ft./sec. | (4)<br>d<br>ft. | (5)<br>$d_c$<br>ft. | (6)<br>F<br>$V/\sqrt{gd}$ | (7)<br>$H_T$<br>ft. | (8)<br>$E_f$<br>ft. | (9)<br>$\eta_f$<br>% | (10)<br>$d_c/H_T$<br>- | (11)<br>$H_T/d$<br>- | (12)<br>$S_n$<br>- | (13)<br>1'/1<br>- | (14)<br>TERMINAL<br>FLOW<br>-STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

TABLE B-3

ROUGHNESS SPACING 2; e - 0.149; H/h = 6.26

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10 | .45 | 1.08 | .340 | .159 | .33 | 4.68 | 0.36 | 92.5 | .034 | 14.0 | - | .51 | # |
| 11 | .80 | 5.33 | .120 | .233 | 2.70 | 4.84 | 0.56 | 88.4 | .048 | 40.2 | - | .40 | 6 |
| 12 | 1.06 | 5.84 | .146 | .282 | 2.70 | 4.95 | 0.68 | 86.3 | .057 | 33.8 | 3.0 | .55 | 6 |
| 14 | 1.39 | 6.60 | .168 | .338 | 2.84 | 5.09 | 0.85 | 83.3 | .067 | 30.2 | 3.0 | .85 | 6 |
| 15 | 1.72 | 7.00 | .197 | .338 | 2.78 | 5.22 | 0.96 | 81.6 | .074 | 26.5 | 4.5 | .85 | 6 |
| 16 | 2.00 | 7.43 | .216 | .430 | 2.82 | 5.35 | 1.08 | 80.0 | .081 | 24.8 | 4.2 | .85 | 6 |
| 17 | 1.49 | 6.74 | .176 | .352 | 2.84 | 5.12 | 0.89 | 82.7 | .069 | 29.1 | - | - | 6 |
| 18 | 1.24 | 6.34 | .157 | .313 | 2.83 | 5.03 | 0.79 | 84.5 | .062 | 32.0 | - | - | 6 |

# Hydraulic jump on every step

(14) Step where terminal condition of flow reached

TABLE B-4

ROUGHNESS SPACING 3; e – 0.122; H/h = Combination Roughness Spacing 1 & 2

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ – | (11) $H_T/d$ – | (12) $S_m$ – | (13) 1'/1 – | (14) TERMINAL FLOW -STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 19 | 0.54 | 1.54 | .280 | .179 | .51 | 4.57 | .32 | 93.1 | .039 | 16.3 | 3.4 | – | #2 |
| 20 | 0.85 | 5.14 | .131 | .244 | 2.50 | 4.73 | .54 | 88.5 | .052 | 36.0 | – | – | #2 |
| 21 | 1.04 | 5.90 | .141 | .278 | 2.77 | 4.83 | .68 | 85.8 | .058 | 34.2 | – | .68 | 4 |
| 22 | 1.13 | 6.19 | .146 | .294 | 2.86 | 4.87 | .75 | 84.5 | .061 | 33.4 | – | .73 | 5 |
| 23 | 1.35 | 6.60 | .164 | .332 | 2.88 | 4.97 | .84 | 83.1 | .067 | 30.3 | – | .73 | 5 |
| 24 | 1.80 | 7.31 | .196 | .400 | 2.92 | 5.15 | 1.03 | 80.0 | .078 | 26.2 | 3.3 | .73 | 5 |
| 25 | 2.00 | 7.79 | .208 | .434 | 3.00 | 5.25 | 1.16 | 78.1 | .083 | 25.2 | 3.0 | .85 | 6 |

# Hydraulic jump on every step

(14) Step where terminal condition of flow reached

## TABLE B-5

| (1)<br>RUN | (2)<br>Q<br>cusecs | (3)<br>V<br>ft./sec. | (4)<br>d<br>ft. | (5)<br>$d_c$<br>ft. | (6)<br>F<br>$V/\sqrt{gd}$ | (7)<br>$H_T$<br>ft. | (8)<br>$E_f$<br>ft. | (9)<br>$\eta_f$<br>% | (10)<br>$d_c/H_T$<br>- | (11)<br>$H_T/d$<br>- | (12)<br>$S_m$<br>- | (13)<br>1'/1<br>- | (14)<br>TERMINAL<br>FLOW<br>-STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROUGHNESS SPACING 4; e - 0.024; H/h = 10 | | | | | | | | | | | | | |
| 30 | .47 | 5.67 | .067 | .164 | 3.86 | 4.52 | .57 | 87.6 | .036 | 67.6 | - | - | 3 |
| 31 | .72 | 6.81 | .084 | .217 | 4.16 | 4.66 | .80 | 82.7 | .047 | 55.6 | - | - | 3 |
| 32 | 1.04 | 7.64 | .110 | .279 | 4.06 | 4.83 | 1.02 | 79.0 | .058 | 43.1 | - | 0.6 | 3 |
| 33 | 1.20 | 7.85 | .123 | .306 | 3.97 | 4.90 | 1.08 | 77.9 | .063 | 39.7 | - | 1.0 | None |
| 34 | 1.40 | 8.14 | .138 | .339 | 3.88 | 4.99 | 1.16 | 76.6 | .068 | 36.1 | - | 1.0 | None |
| 35 | 1.89 | 8.89 | .170 | .411 | 3.80 | 5.18 | 1.40 | 73.0 | .079 | 30.4 | - | 1.0 | None |
| 36 | 2.00 | 9.50 | .175 | .430 | 3.99 | 5.24 | 1.58 | 69.1 | .082 | 29.9 | - | 1.0 | None |

(14) Step where terminal conditions of flow reached

## TABLE B-6

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ - | (11) $H_T/d$ - | (12) $S_m$ - | (13) 1'/1 - | (14) TERMINAL FLOW -STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROUGHNESS SPACING 5; e - 0.138; H/h = 15 | | | | | | | | | | | | | |
| 48 | .45 | 5.42 | .067 | .159 | 3.70 | 4.51 | .53 | 88.4 | .035 | 67.5 | 4.4 | .42 | 5 |
| 49 | .86 | 5.92 | .116 | .245 | 3.07 | 4.73 | .67 | 86.0 | .052 | 40.7 | - | .58 | 8 |
| 50 | 1.11 | 6.38 | .138 | .290 | 3.22 | 4.85 | .77 | 84.2 | .060 | 35.2 | - | .64 | 8 |
| 51 | 2.00 | 7.54 | .213 | .429 | 2.88 | 5.26 | 1.09 | 79.2 | .082 | 24.7 | 2.3 | - | 8 |
| 52 | 1.78 | 7.09 | .202 | .398 | 2.78 | 5.16 | .98 | 81.1 | .077 | 25.5 | - | - | 8 |
| 53 | 1.49 | 6.73 | .176 | .352 | 2.83 | 5.03 | .89 | 82.5 | .070 | 28.6 | - | - | 8 |

(14) Step where terminal conditions of flow reached

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ - | (11) $H_T/d$ - | (12) $S_m$ - | (13) 1'/1 - | (14) TERMINAL FLOW -STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

## TABLE B-7

ROUGHNESS SPACING 6; e - 0.200; H/h = 11.42

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 54 | 2.00 | 7.32 | .219 | .430 | 2.76 | 5.32 | 1.05 | 80.3 | .081 | 24.3 | 2.3 | - | 8 |
| 55 | 1.83 | 7.00 | .210 | .404 | 2.70 | 5.24 | 0.97 | 81.5 | .077 | 24.9 | 2.5 | - | 8 |
| 56 | 1.62 | 6.76 | .191 | .372 | 2.72 | 5.16 | 0.90 | 82.5 | .072 | 27.0 | 2.7 | - | 8 |
| 57 | 1.18 | 6.06 | .155 | .302 | 2.71 | 4.95 | 0.73 | 85.3 | .061 | 31.9 | - | .58 | 6 |
| 58 | 1.48 | 6.20 | .193 | .354 | 2.49 | 5.09 | 0.79 | 84.4 | .070 | 26.4 | - | 1.00 | 6 |
| 59 | .59 | 4.54 | .105 | .191 | 2.48 | 4.68 | 0.43 | 90.9 | .041 | 44.5 | 2.7 | .48 | 6 |
| 60 | .91 | 5.42 | .135 | .255 | 2.61 | 4.83 | 0.60 | 87.8 | .053 | 35.7 | - | .51 | 5 |

# Hydraulic jump on every step

(14) Step where terminal conditions of flow reached

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ - | (11) $H_T/d$ - | (12) $S_m$ - | (13) 1'/1 - | (14) TERMINAL FLOW -STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|

TABLE B-8

ROUGHNESS SPACING 7; e - 0.09; H/h = 11.42

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 61 | 2.00 | 7.43 | .217 | .432 | 2.80 | 5.32 | 1.08 | 79.8 | .081 | 24.5 | 1.85 | - | 6 |
| 62 | 1.78 | 7.00 | .204 | .397 | 2.74 | 5.20 | 0.96 | 81.4 | .076 | 25.5 | - | - | 6 |
| 63 | 1.49 | 6.50 | .184 | .354 | 2.67 | 5.09 | 0.84 | 83.4 | .070 | 27.6 | 2.00 | .58 | 6 |
| 64 | 1.28 | 6.14 | .166 | .311 | 2.66 | 4.99 | 0.76 | 84.9 | .064 | 30.0 | - | .54 | 6 |
| 65 | 1.08 | 5.65 | .152 | .284 | 2.56 | 4.90 | 0.65 | 86.8 | .058 | 32.2 | - | - | 6 |
| 66 | 0.92 | 5.35 | .138 | .256 | 2.54 | 4.83 | 0.58 | 87.9 | .053 | 34.9 | - | - | 6 |
| 67 | 0.48 | 1.24 | .310 | .166 | 0.39 | 4.62 | 0.33 | 92.8 | .036 | 14.9 | 2.60 | - | 6 |

# Hydraulic jump on every step

(14) Step where terminal conditions of flow reached

TABLE B-9

ROUGHNESS SPACING 8; e - 0.185; H/h = 20

| (1)<br>RUN | (2)<br>Q<br>cusecs | (3)<br>V<br>ft./sec. | (4)<br>d<br>ft. | (5)<br>$d_c$<br>ft. | (6)<br>F<br>$V/\sqrt{gd}$ | (7)<br>$H_T$<br>ft. | (8)<br>$E_f$<br>ft. | (9)<br>$\eta_f$<br>% | (10)<br>$d_c/H_T$<br>- | (11)<br>$H_T/d$<br>- | (12)<br>$S_m$<br>- | (13)<br>1'/1<br>- | (14)<br>TERMINAL<br>FLOW<br>-STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 68 | 2.00 | 7.85 | .204 | .430 | 3.07 | 5.26 | 1.17 | 77.8 | .082 | 25.8 | 1.1 | - | NONE |
| 69 | 1.80 | 7.48 | .193 | .400 | 3.00 | 5.15 | 1.06 | 79.4 | .078 | 26.8 | 1.3 | - | NONE |
| 70 | 1.59 | 7.15 | .179 | .367 | 3.01 | 5.07 | 0.97 | 80.9 | .072 | 28.8 | 1.4 | - | NONE |
| 71 | 1.24 | 6.31 | .157 | .313 | 2.82 | 4.92 | 0.78 | 84.2 | .064 | 31.4 | 1.6 | - | NONE |
| 72 | 1.05 | 5.83 | .144 | .280 | 2.71 | 4.83 | 0.67 | 86.1 | .058 | 33.6 | 1.8 | - | NONE |
| 73 | 0.90 | 5.55 | .129 | .252 | 2.72 | 4.76 | 0.61 | 87.2 | .053 | 37.0 | 2.0 | - | NONE |
| 74 | 0.36 | 1.16 | .250 | .137 | 0.41 | 4.46 | 0.27 | 93.9 | .031 | 17.9 | - | - | NONE |
| 75 | 0.58 | 5.00 | .093 | .185 | 2.89 | 4.59 | 0.48 | 89.5 | .040 | 49.2 | - | - | NONE |

(14) Step where terminal conditions of flow reached

## TABLE B-10

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ - | (11) $H_T/d$ - | (12) $S_m$ - | (13) 1'/1 - | (14) TERMINAL FLOW -STEP- |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROUGHNESS SPACING 9; e - 0.065; H/h = 7 | | | | | | | | | | | | | |
| 76 | 2.00 | 8.54 | .188 | .430 | 3.47 | 5.26 | 1.33 | 74.9 | .082 | 28.0 | 1.5 | .48 | 4 |
| 77 | 1.83 | 8.27 | .177 | .405 | 3.47 | 5.17 | 1.24 | 76.1 | .078 | 29.2 | 1.6 | .46 | 4 |
| 78 | 1.58 | 7.90 | .160 | .367 | 3.50 | 5.07 | 1.13 | 77.8 | .027 | 31.6 | 1.8 | .45 | 4 |
| 79 | 1.43 | 7.68 | .149 | .344 | 3.50 | 5.00 | 1.07 | 78.6 | .069 | 33.5 | 1.7 | .48 | 4 |
| 80 | 1.18 | 7.05 | .134 | .302 | 3.39 | 4.88 | 0.90 | 81.4 | .062 | 36.4 | 2.0 | .48 | 4 |
| 81 | 0.63 | 5.59 | .091 | .198 | 3.27 | 4.62 | 0.58 | 87.5 | .043 | 50.8 | 2.0 | - | 4 |
| 82 | 1.00 | 6.65 | .120 | .271 | 3.40 | 4.80 | 0.81 | 83.1 | .057 | 39.9 | - | - | 4 |

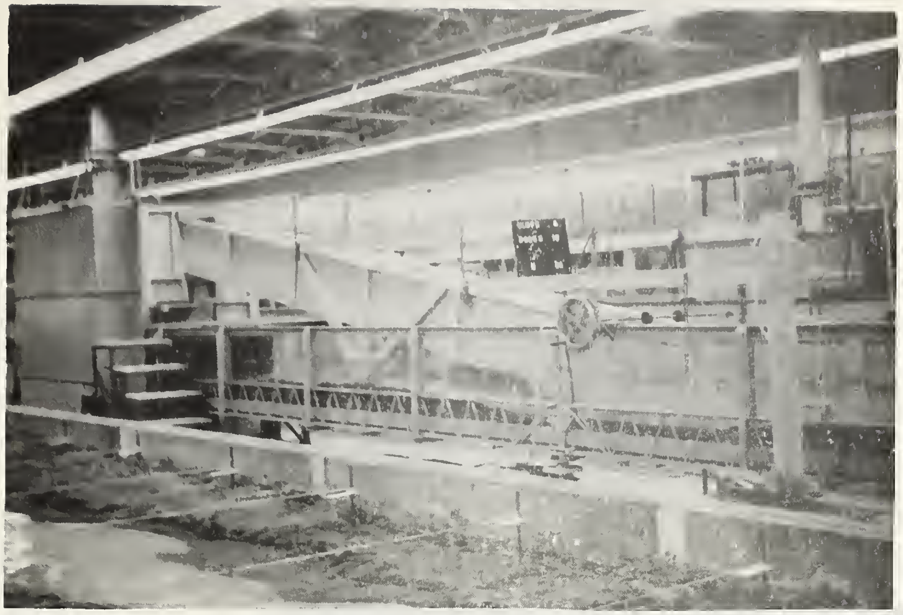
(14) Step where terminal conditions of flow reached

TABLE B-11

| (1) RUN | (2) Q cusecs | (3) V ft./sec. | (4) d ft. | (5) $d_c$ ft. | (6) F $V/\sqrt{gd}$ | (7) $H_T$ ft. | (8) $E_f$ ft. | (9) $\eta_f$ % | (10) $d_c/H_T$ – | (11) $H_T/d$ – | (12) $S_m$ – | (13) 1'/1 – | (14) TERMINAL FLOW STEP |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ROUGHNESS SPACING 10; e – 0.075; H/h = 10 | | | | | | | | | | | | | |
| 83 | 2.00 | 7.42 | .217 | .431 | 2.80 | 5.27 | 1.07 | 79.6 | .082 | 24.2 | .75 | 1.00 | 4 |
| 84 | 1.80 | 7.03 | .204 | .400 | 2.74 | 5.16 | 0.97 | 81.2 | .078 | 25.3 | .75 | 1.00 | 4 |
| 85 | 1.48 | 6.30 | .187 | .350 | 2.58 | 5.03 | 0.81 | 84.0 | .070 | 26.9 | .75 | 1.00 | 4 |
| 86 | 1.18 | 5.73 | .165 | .302 | 2.48 | 4.90 | 0.68 | 86.3 | .062 | 29.7 | .75 | 1.00 | 4 |
| 87 | 0.82 | 4.57 | .144 | .236 | 2.13 | 4.72 | 0.47 | 90.1 | .050 | 32.8 | .75 | 1.00 | 4 |
| 88 | 0.50 | 1.43 | .280 | .171 | 0.48 | 4.55 | 0.31 | 93.2 | .038 | 16.3 | .75 | – | 4 |

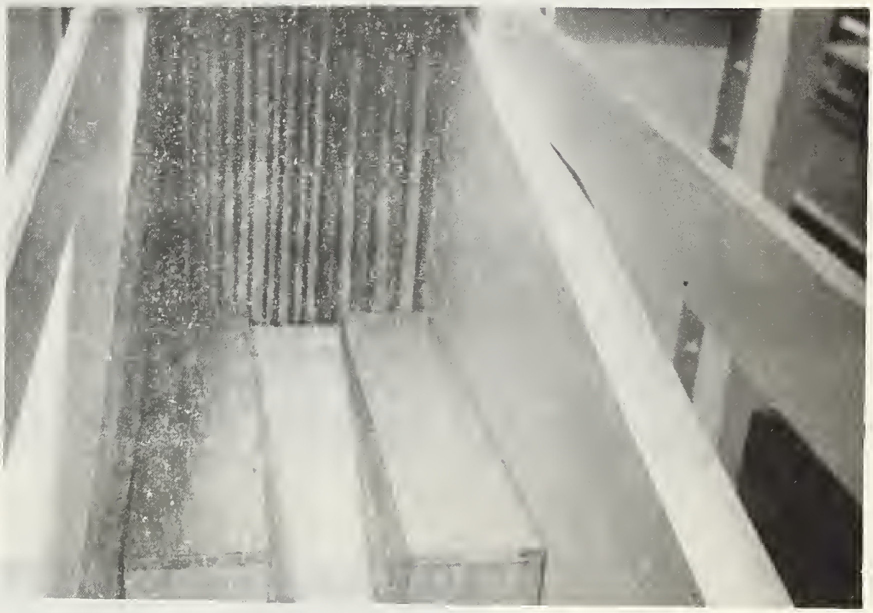
(14) Step where terminal conditions of flow reached

# APPENDIX C



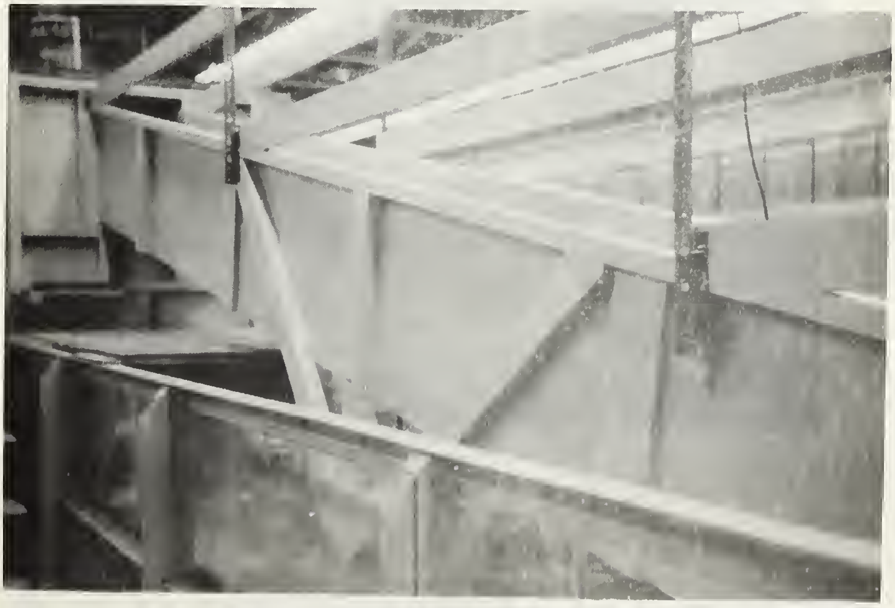
PHOTOGRAPH C–I

ENTRANCE TANK, FLUME AND OVER–ALL SET–UP.



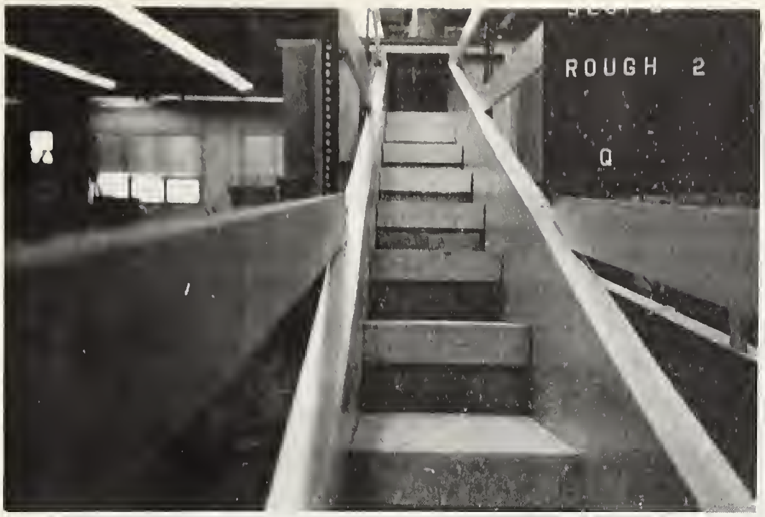
PHOTOGRAPH C–2

BAFFLES IN ENTRANCE TANK, AND ALSO SHOWING PART OF ROUGHNESS SPACING I0 DESIGN.



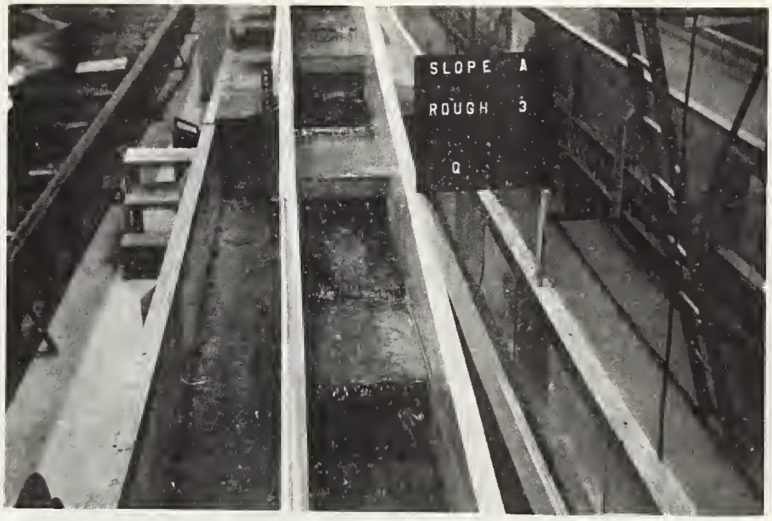
PHOTOGRAPH C–3

VIEW OF DATUM BOARDS AND FLUME



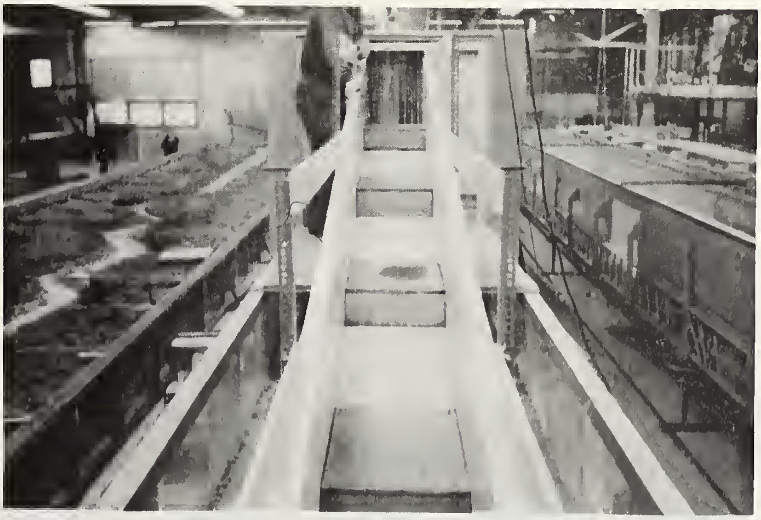
PHOTOGRAPH C–4

ROUGHNESS SPACING
2



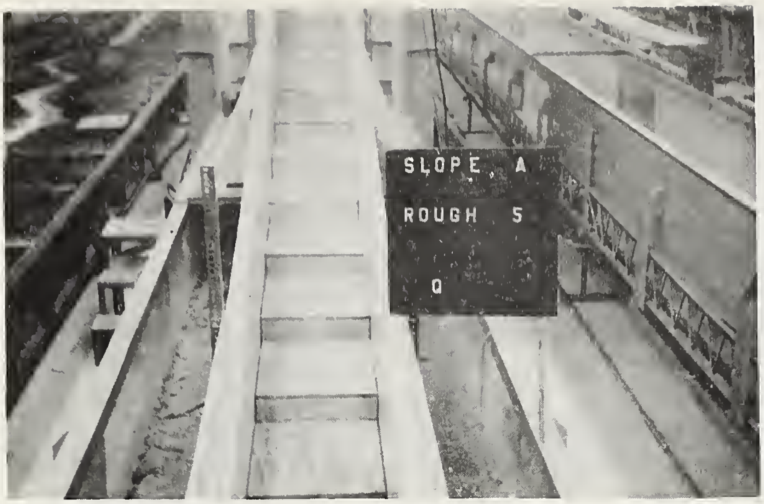
PHOTOGRAPH C–5

ROUGHNESS SPACING
3



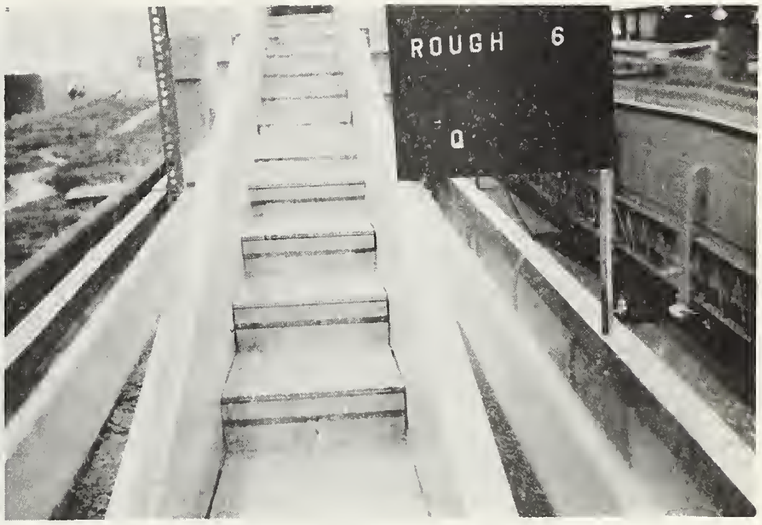
PHOTOGRAPH C- 6

ROUGHNESS SPACING
4



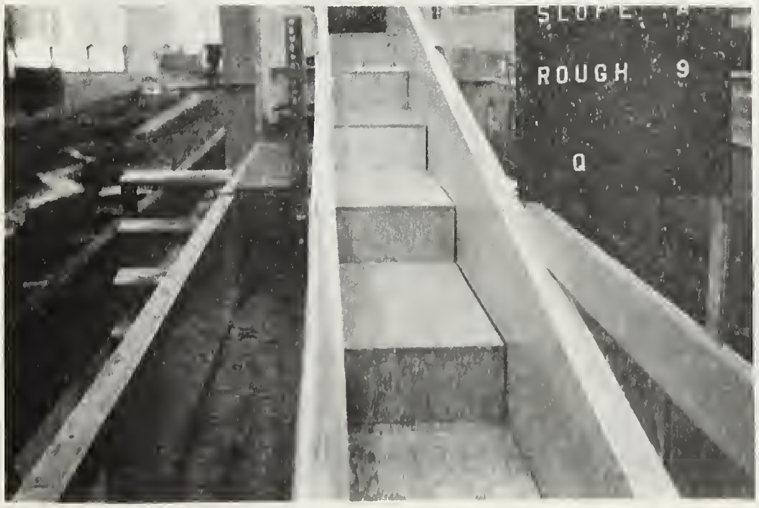
PHOTOGRAPH C–7

ROUGHNESS SPACING
5



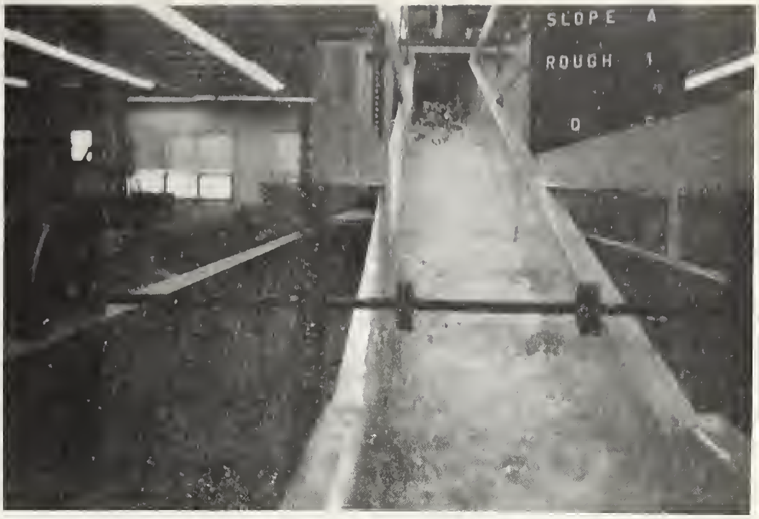
PHOTOGRAPH C–8

ROUGHNESS SPACING
6



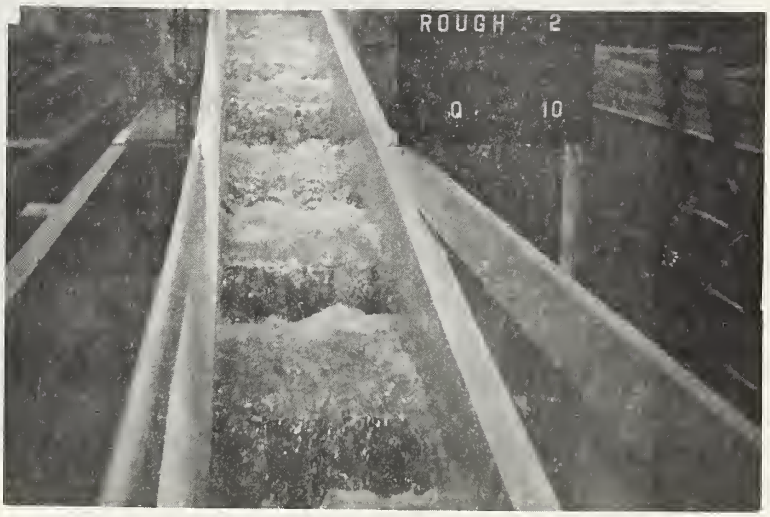
PHOTGRAPH C–9

ROUGHNESS SPACING
9



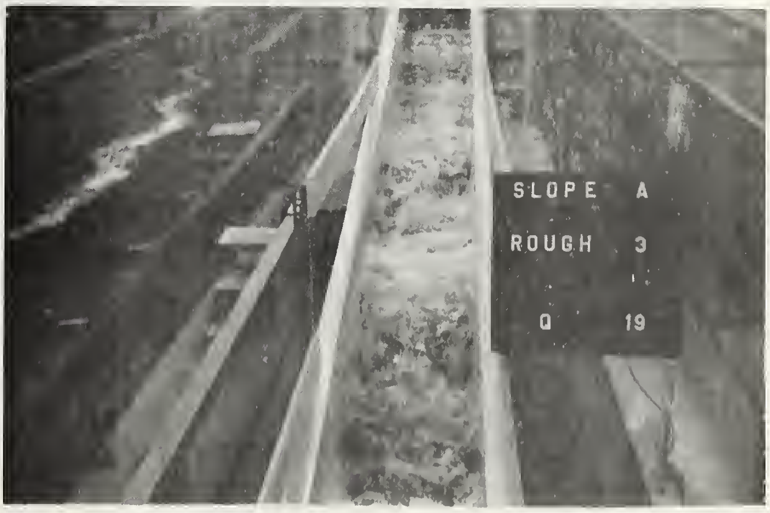
PHOTOGRAPH C–10

RUN 6– ROUGHNESS SPACING 1.



PHOTOGRAPH C–11

RUN 10– ROUGHNESS SPACING 2.



PHOTOGRAPH C–12

RUN 19– ROUGHNESS SPACING 3.

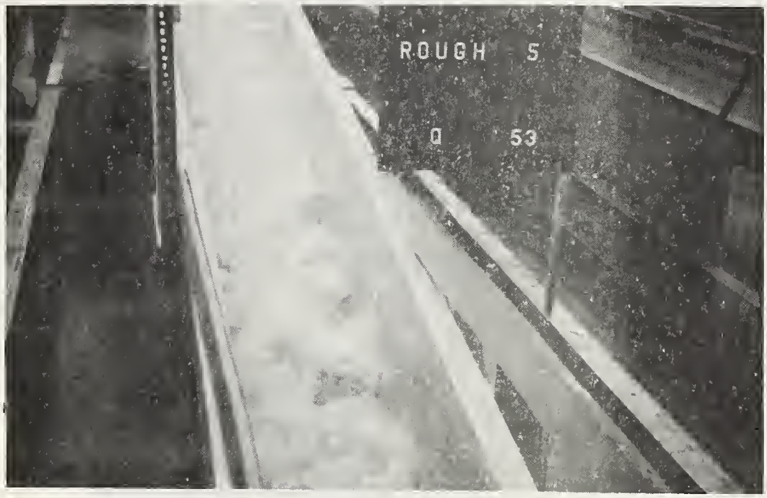
[illegible]

[illegible]

[illegible]

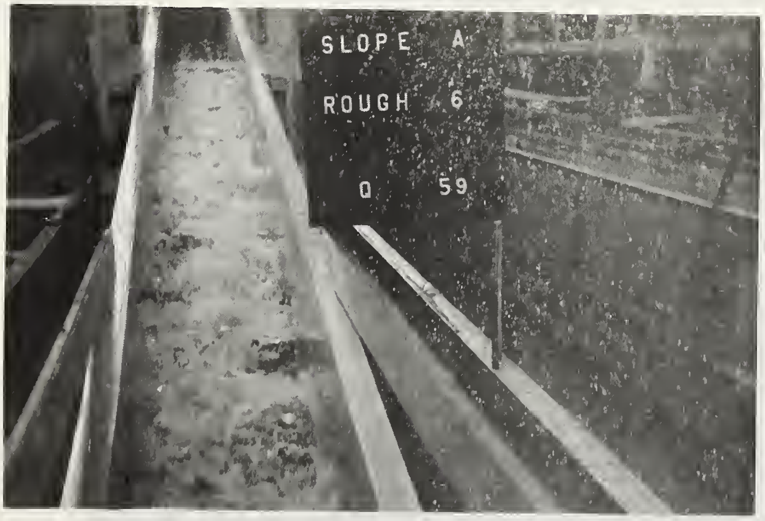
PHOTOGRAPH C–13

RUN 34– ROUGHNESS SPACING 4.



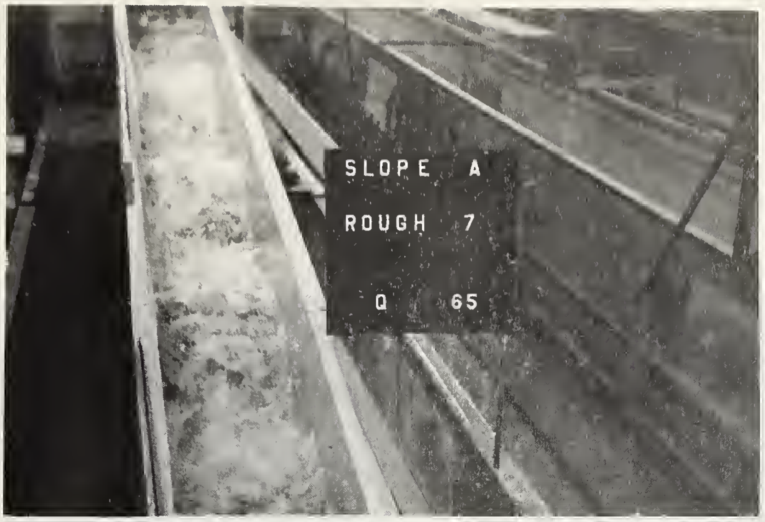
PHOTOGRAPH C–14

RUN 53– ROUGHNESS SPACING 5.



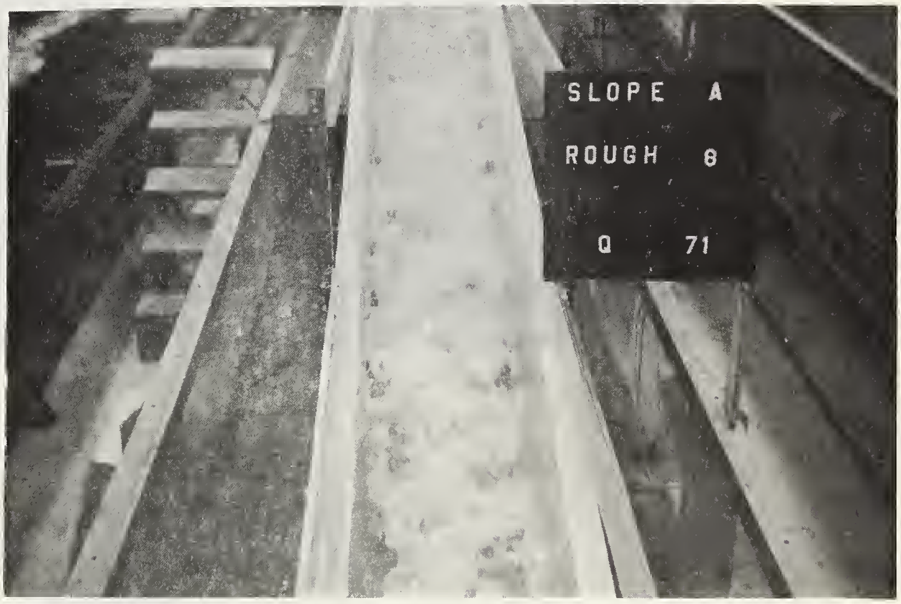
PHOTOGRAPH C–15

RUN 59– ROUGHNESS SPACING 6.



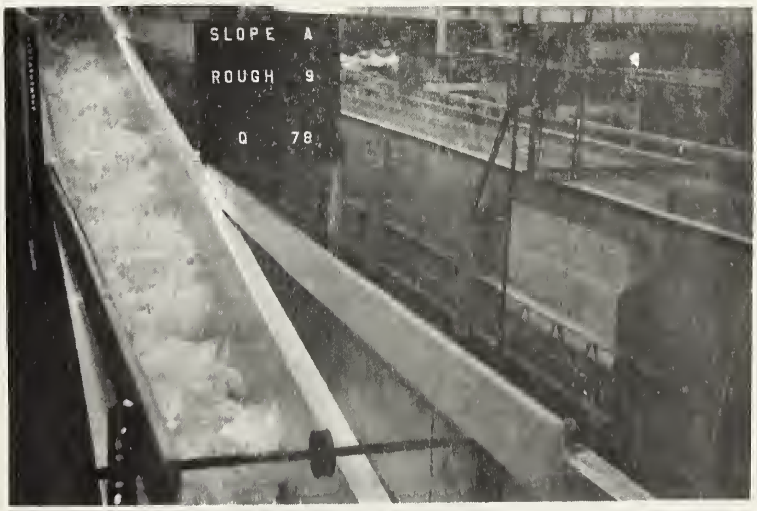
PHOTOGRAPH C–16

RUN 65– ROUGHNESS SPACING 7.



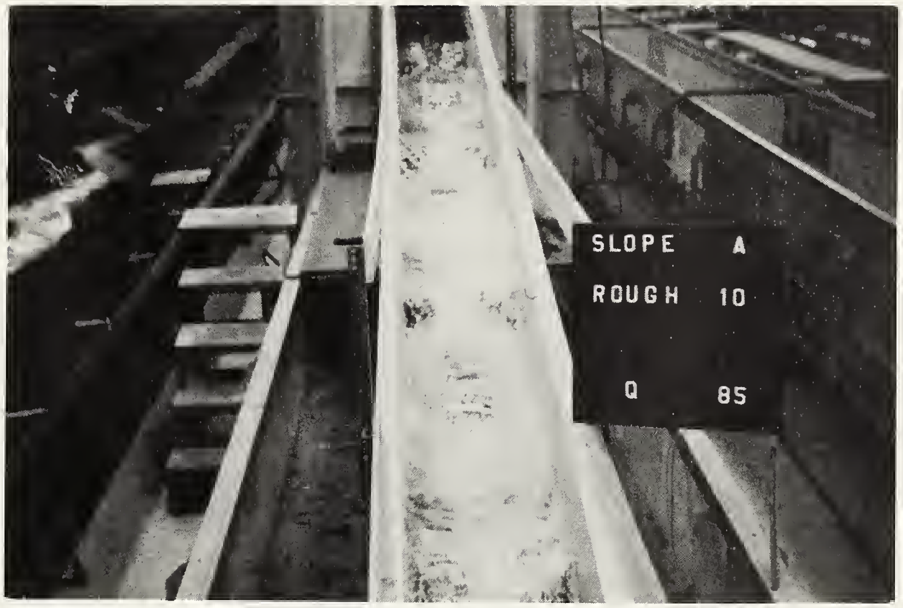
PHOTOGRAPH C–17

RUN 71– ROUGHNESS SPACING 8.



PHOTOGRAPH C–18

RUN 78– ROUGHNESS SPACING 9.



PHOTOGRAPH C-19

RUN 85– ROUGHNESS
SPACING 10.

# APPENDIX D

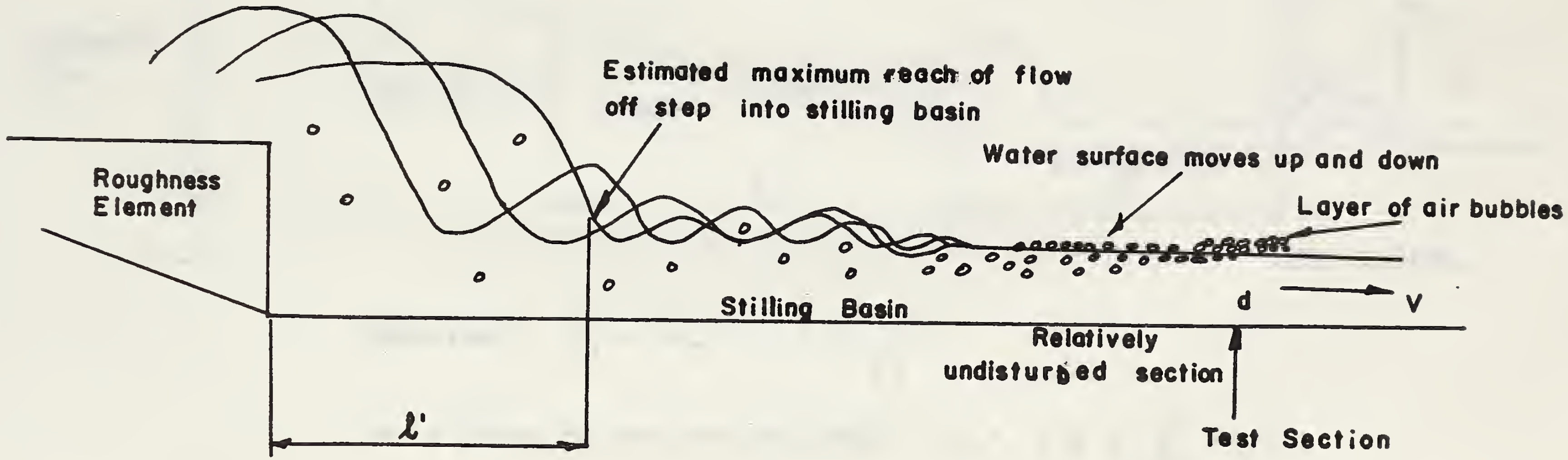
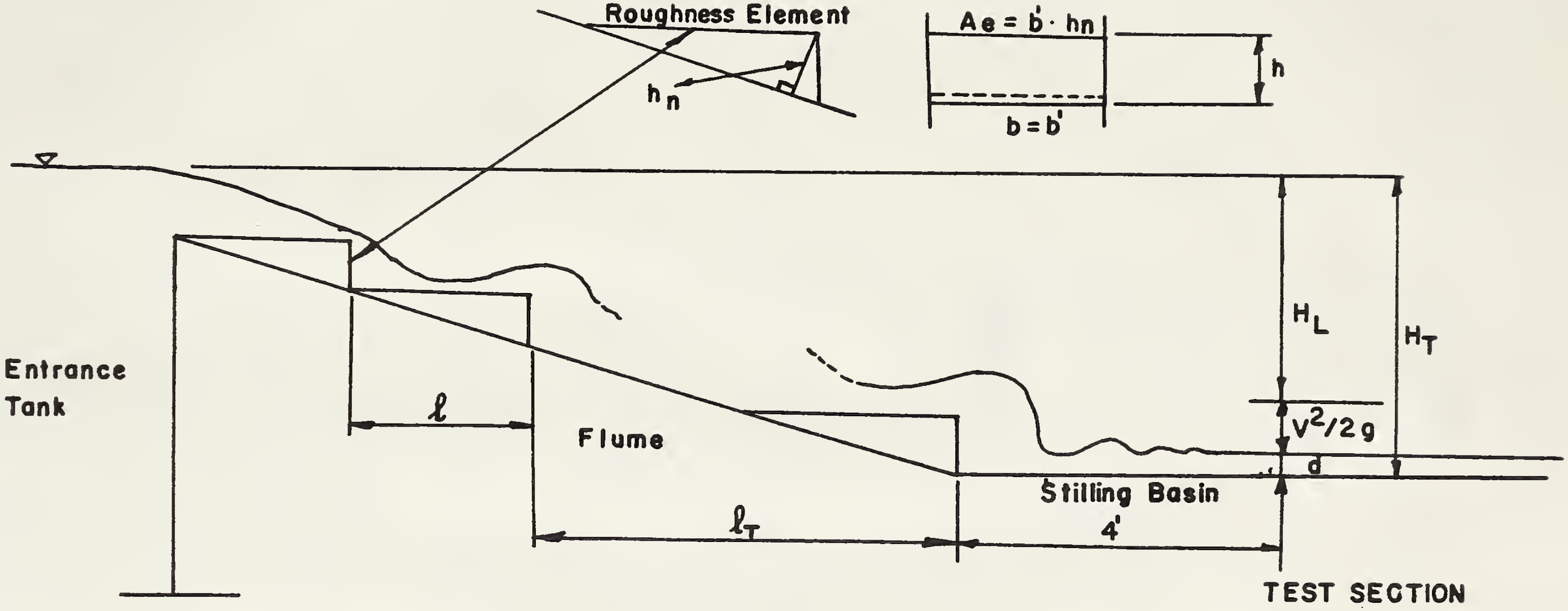


FIGURE · D·1 TYPICAL FLOW CONDITIONS DOWNSTREAM



Head loss $= H_L = H_T - \left( d + \frac{V^2}{2g} \right)$

where Energy of flow at test section $= E_f = \left( d + \frac{V^2}{2g} \right)$

Efficiency of energy dissipation $= \eta_f = \left( \frac{H_L}{H_T} \right) 100\ \%$

FIGURE D · 2

[illegible]

[illegible]

[illegible]

[illegible]

# APPENDIX E

# APPENDIX E

## Example Calculation to Find Mean Depth

E.1.1 Data Given:

- The velocity profile at the test section, FIGURE E-1.
- The criterion that the mean velocity of flow at a section is the average of the velocities at 0.20 and 0.80 of the mean depth of flow, on the velocity profile, Chow, (1959).
- The mean velocity of flow (V), at the test section should also equal q/d, where q is the discharge intensity and d is the mean depth of flow.
- Discharge intensity is 1.26 cusecs per foot.
- Assume that we have a wide channel, i.e. the velocity profile given above will be the same at any point along the test section.

E.1.2 Calculations:

(i) Estimate the mean depth of flow to be 0.17 feet.

(ii) Using the given velocity profile, it is found that the velocities at 0.80 and 0.20 of the above assumed mean depth are 7.33 ft./sec. and 6.90 ft./sec., respectively.

(iii) The average of these is 7.12 ft./sec., so V = 7.12 ft./sec.

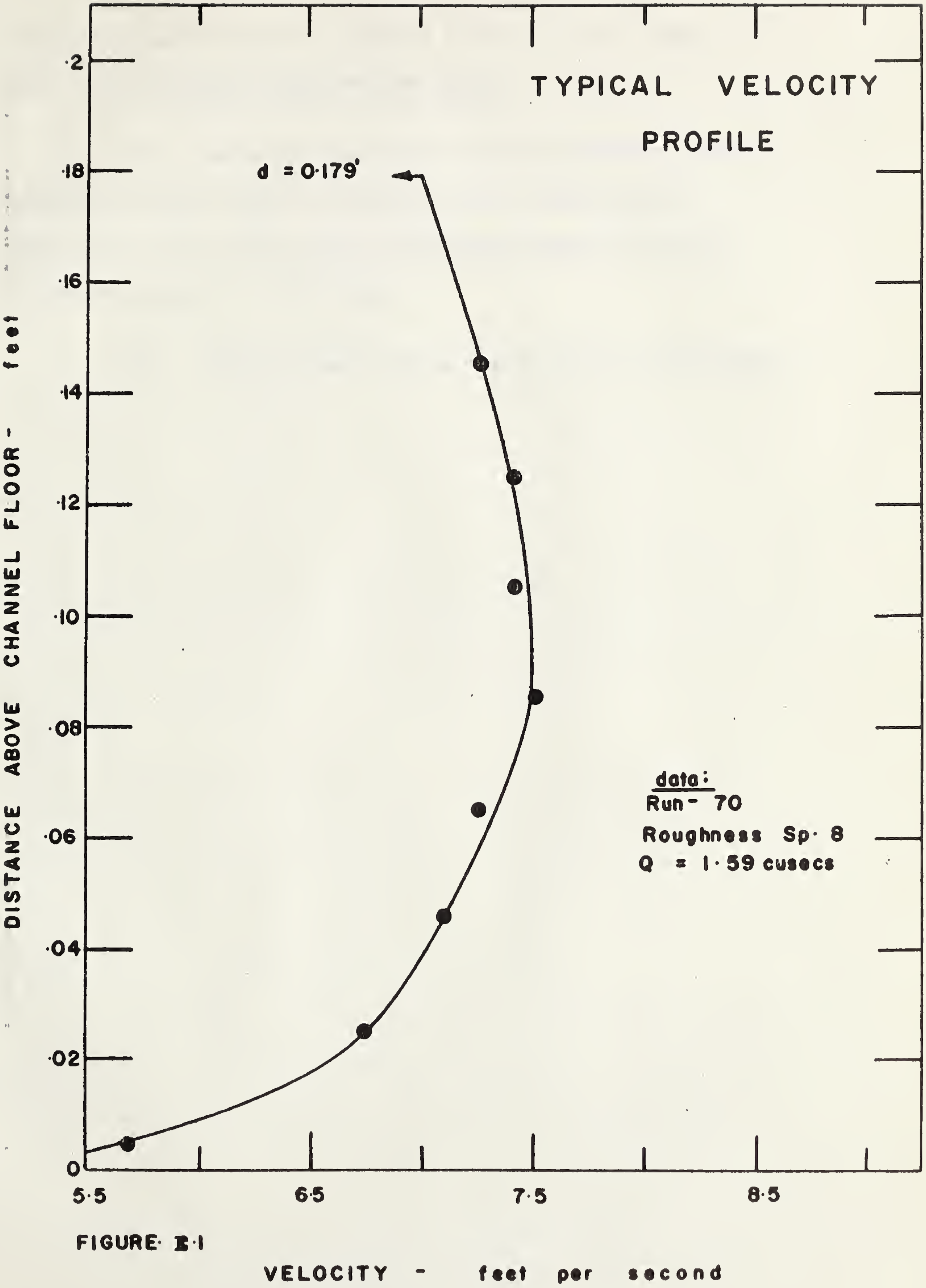
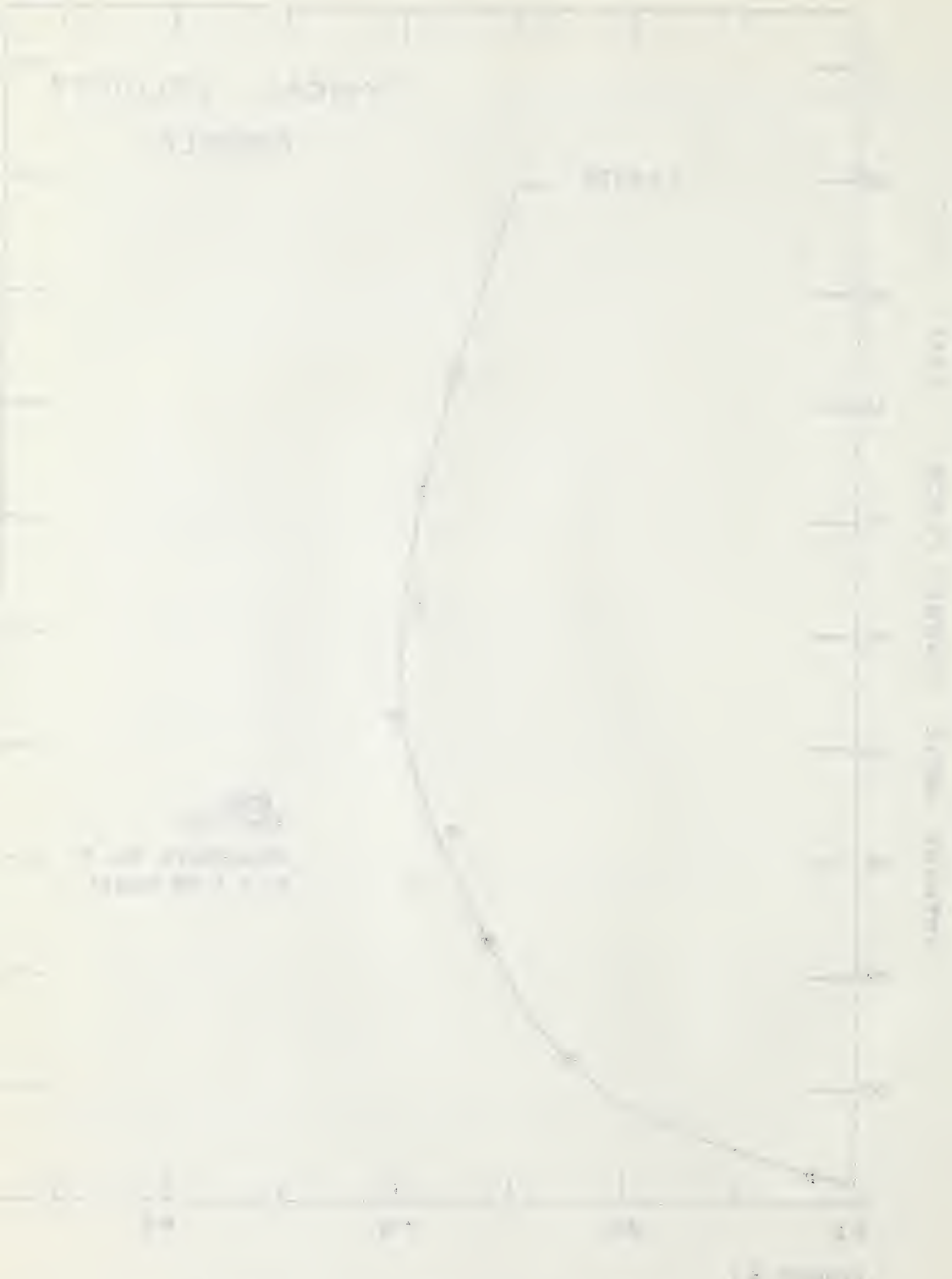

TYPICAL VELOCITY PROFILE
d = 0·179'
data:
Run- 70
Roughness Sp· 8
Q = 1·59 cusecs
DISTANCE ABOVE CHANNEL FLOOR - feet
·2
·18
·16
·14
·12
·10
·08
·06
·04
·02
0
5·5
6·5
7·5
8·5
VELOCITY - feet per second

FIGURE E·1



[illegible]

This should equal V = q/d = 1.26/0.71 = 7.48 ft./sec. Therefore, the assumed mean depth was too small.

(iv) Assume d = 0.179 ft. Using the velocity profile gives 6.93 ft./sec. and 7.24 ft./sec. at the 0.20 and 0.80 depth of d, so V = 7.09 ft./sec. This should equal V = q/d = 1.26/0.179 ft./sec. = 7.09 ft./sec.

(v) The mean depth of flow for this run is 0.179 feet.

# APPENDIX E

## Example Design of a Canal Drop Structure

E.2.1 A canal drop is to be designed for 70 cusecs per foot, where the drop from the crest to be downstream floor level is 60 feet and chute slope is 1:2. The following alternative designs will be considered:

(i) The drop will consist of a concrete, rectangular chute and stilling basin. No chute blocks or baffle piers are used in the stilling basin. The floor is horizontal at the elevation of the original ground surface.

(ii) The drop will consist of a concrete, rectangular chute and stilling basin, with the chute comprised of a continuous series of standard steps. As an aid in this analysis, the following design curves are introduced:

FIGURE E-2: A graph of the ratio of tailwater depth to depth of flow before a hydraulic jump, versus the Froude Number of flow there. Therefore, knowing the initial depth and velocity of flow at the base of a chute, the sequent depth or tailwater depth required to force a jump to occur can be estimated.

FIGURE E-3: A graph of the ratio of the length of jump to the mean depth of flow upstream of the jump versus the Froude Number of flow there. From this curve, the resultant length of jump can be

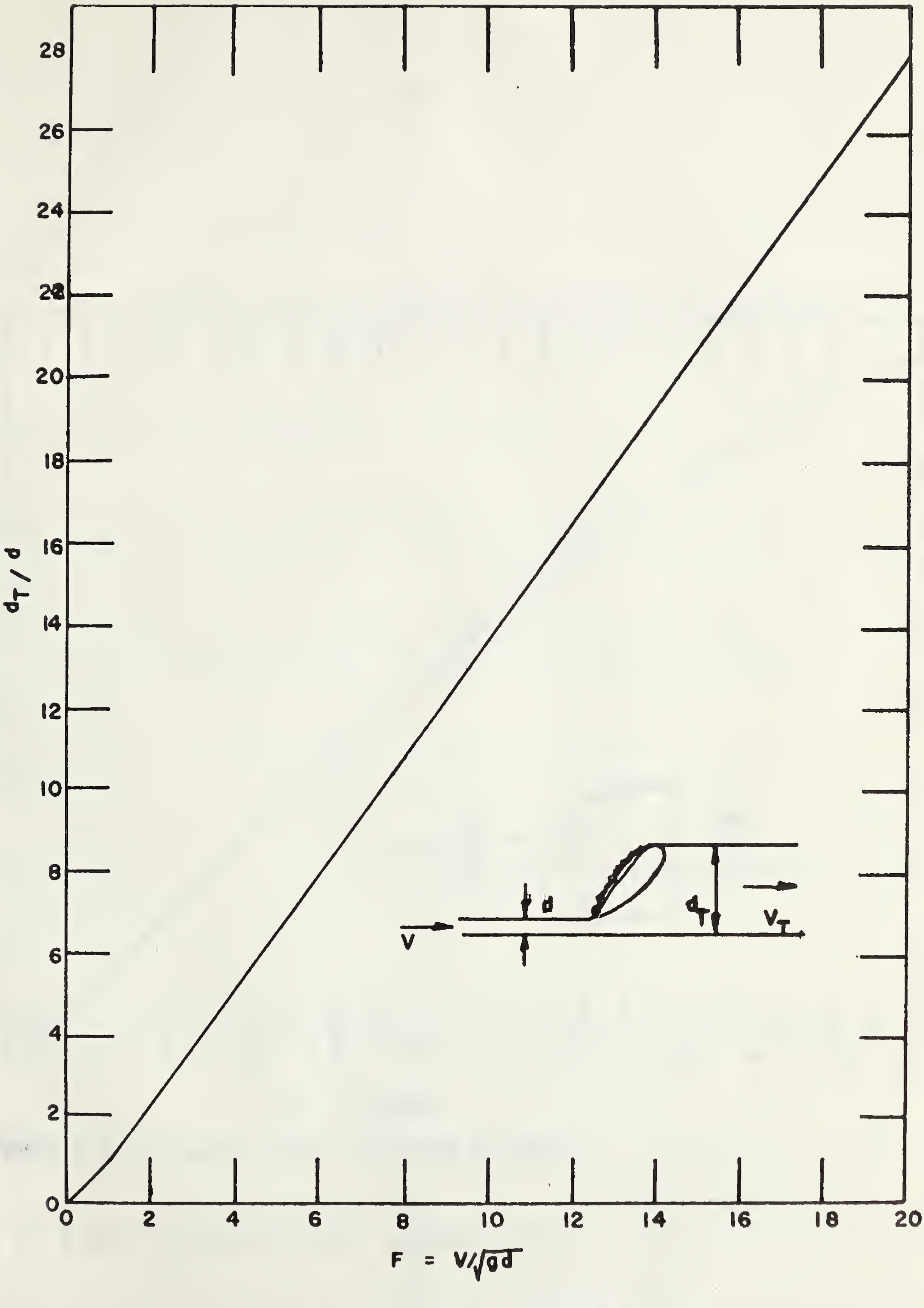


FIGURE- E·2 - Taken from PETERKA, (1963)
TO FIND REQUIRED TAIL-WATER DEPTH ($d_T$)

[illegible]

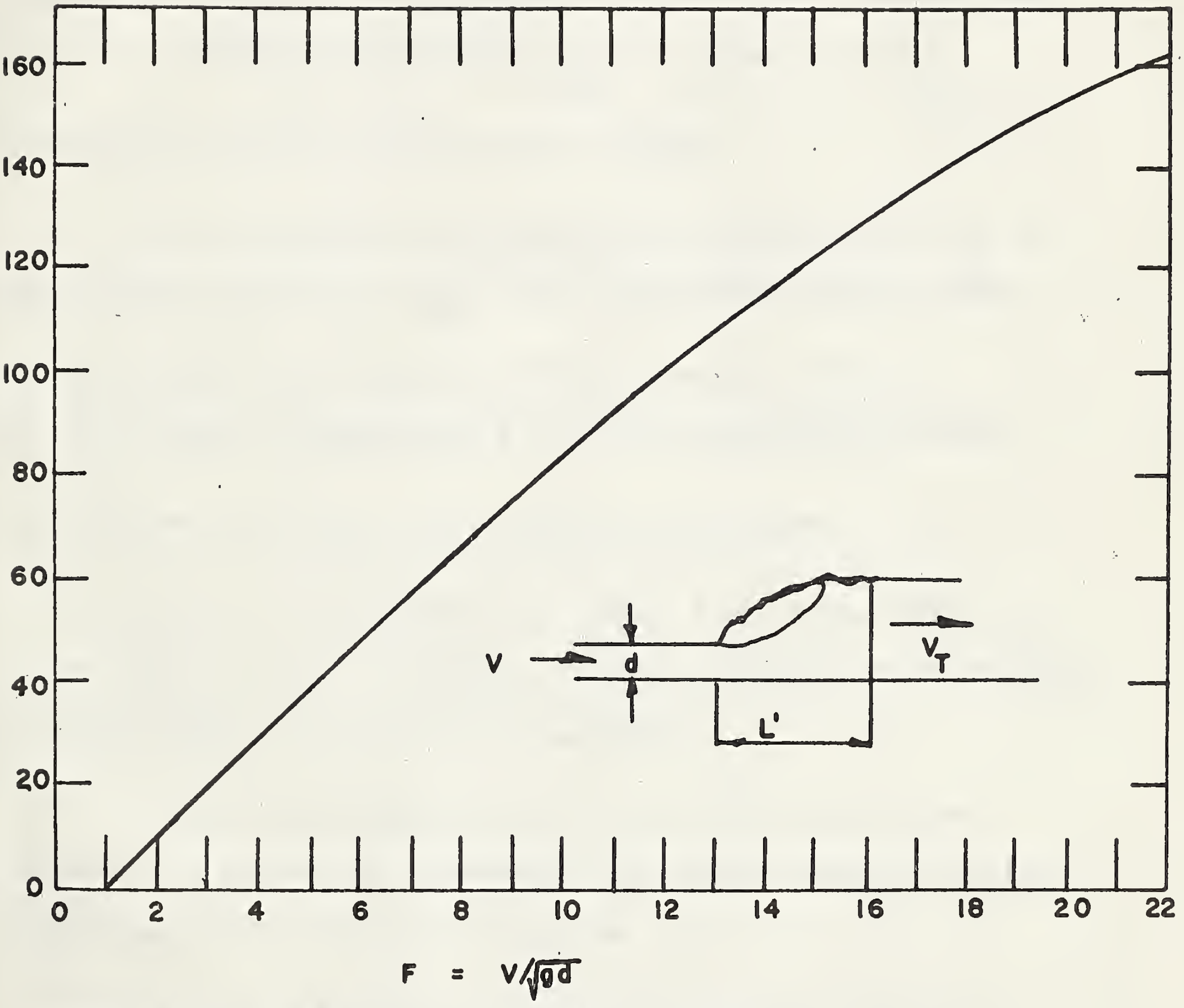


FIGURE - E3 - Taken from PETERKA, (1963)

TO FIND LENGTH OF JUMP (L')

[illegible]

[illegible]

[illegible]

calculated, and this can be taken as the distance from the upstream end or front of the jump to where the flow becomes fairly uniform. For design purposes, the length of jump fixes the end of the concrete floor and sidewalls of a stilling basin.

Calculations, Alternative 1:

E.2.2 (i) Critical depth for q = 70 cusecs per ft. is 5.34 feet. Assuming that the depth over upstream crest is critical, then the total head $H_T$ can be approximately by $(d_c + \frac{V_c^2}{2g} + H)$, where $V_c = q/d_c$. Therefore, $H_T = (5.34' + 2.67' + 60') = \underline{68 \text{ feet}}$.

(ii) Writing the energy equation at the end of the chute in the stilling basin $H_T = (d + \frac{V^2}{2g} + H_L)$, and assuming friction losses $H_L'$, on the chute are 0.15 $H_T$ or 10.20 feet, then $H_T$ = 68 ft. = $(d + \frac{V^2}{2g} + 10.20')$. Substituting d = q/V, and solving for d, we get d = 1.16 feet, and also V = q/d = 70/1.16 = 60.4 ft/sec

(iii) The Froude Number $(V/\sqrt{gd})$ = 9.90. Using FIGURE E-2 for F = 9.90, the ratio of tailwater depth to d is 13.50, or the required tailwater depth $d_T$ is (13.50)1.16 = $\underline{15.65 \text{ feet}}$.

(iv) Using FIGURE E-3, for F = 9.90, the ratio of jump length to d is equal to 84. Therefore, the required length of stilling basin is about 84 (1.16) or L' = 97.4 feet.

(v) Total head loss from the upstream crest to the end of

the stilling basin ($H_L$), is then($H_L' + E_f - E_T$), where $E_f = d + \frac{V^2}{2g} =$ $1.16 + \frac{60.4^2}{2g} = 57.8$ ft. and $E_T = d_T + \frac{V_T^2}{2g} = 15.65 + \left(\frac{70}{15.65}\right)^2 . \frac{1}{2g} =$ 15.96 ft. Therefore, $H_L = 10.20 + 57.8 + 15.96 =$ 52.3 ft.

(vi) The efficiency of energy dissipation is then $H_L/H_T$ (100) or $\eta_f = 52.3/68\ (100) = 76.5\%$.

Calculations, Alternative 2:

E.2.3 (i) Since $d_c/H_T = 5.34/60 = 0.089$, then from PARAGRAPH (3.15.i), the design for a cascade will include a series of roughness elements made up of 15 standard steps. Since H/h = 15 = 4 ft. then the step height will be 4 feet. Also step length "l" will be 120/15 = 8 feet.

(ii) Using EQUATION 3.15.1, Where $d = \frac{d_c^{0.91} . H_T^{0.09}}{2.51}$, and where $d_c = 5.34$ ft. and $H_T = 68$ feet, then the resultant depth of flow in the stilling basin, where flow is relatively undisturbed, is $d = \frac{5.34^{0.91} . 68^{0.09}}{2.51} = 3.05$ feet. Therefore, the energy of flow there is $Ef = d + \frac{V^2}{2g} = 3.05 + (70/3.05)^2 . \frac{1}{2g} = 11.28$ ft. and the energy loss due to the cascade is then 68 - 11.28 = 56.7 feet.

(iii) If it is desired to have a hydraulic jump form in the stilling basin with the above conditions of flow, where the Froude Number of flow is $F = V/\sqrt{gd} = \frac{(70/3.05)}{32.2(3.05)} = 2.32$, then from FIGURE E-2, we find that the required tailwater depth is $(d_T/d)d =$

2.80 (3.05) = 8.5 feet. Also, from FIGURE E-3, the required length of stilling basin should be about (L'/d)d = (13) 3.05 = 40 feet. To obtain a better estimate of the required length of stilling basin, the estimated length 1', (FIGURE D-1) should be added to the above 40 feet. From TABLE 2.3, 1'/1 = 0.55, where "1" = 8 feet, so that 1' = 8(0.55) = 4.40 feet, say 5.0 feet. Therefore, the length of stilling basin should be about 40 + 5 = 45 feet.

(iv) Additional energy loss over the jump is $(11.28 - (8.5 - \frac{70^2}{8.5^2} \cdot \frac{1)}{2g} = 1.73$ feet. Total head loss from upstream crest to the downstream end of the stilling basin is 56.7 ft. + 1.73 ft. = 58.4 feet, or the efficiency of energy dissipation is $\eta_f$ = 58.4/68 (100) = 86%. The cascade is responsible for dissipating 56.7/68 (100) = 83.4% of the total head $H_T$.

### E.2.4 Summation

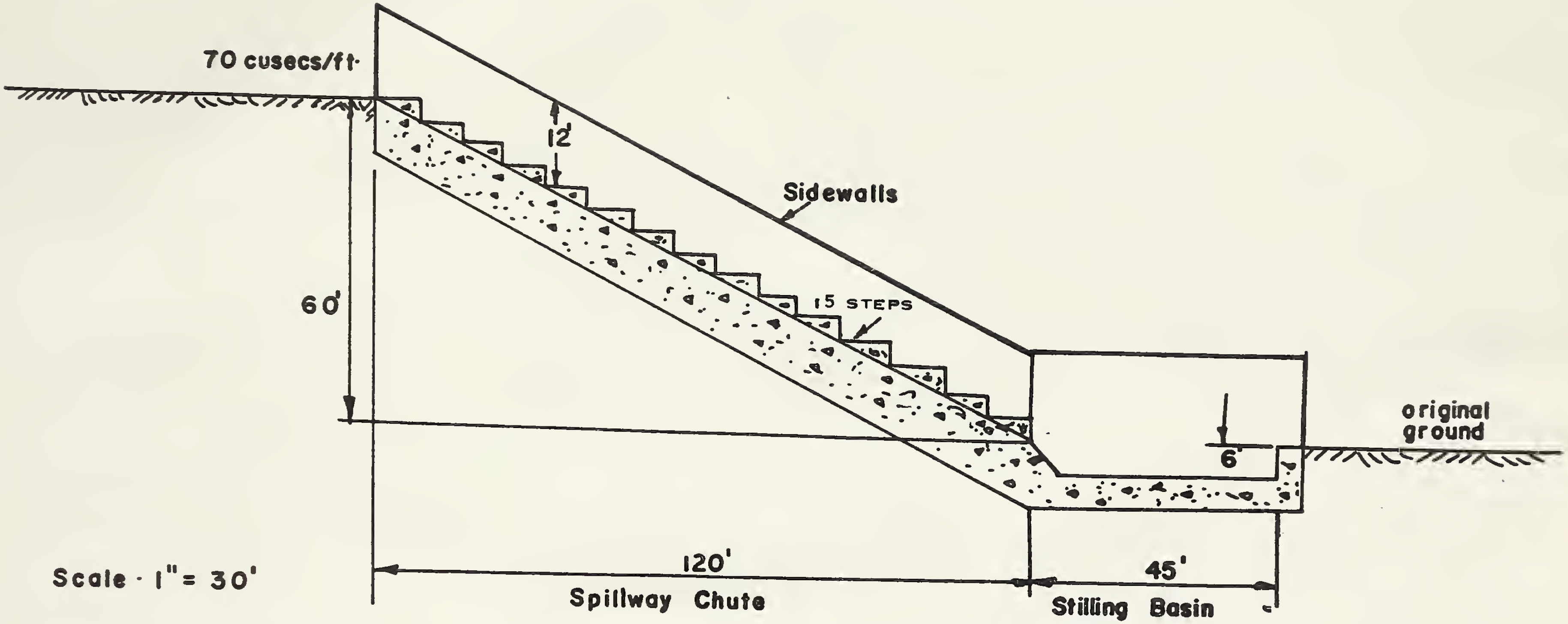
| | L' (length basin) feet | $d_T$ (required tailwater) depth feet | $\eta_f$ (total) % | $\eta_f$ (cascades) % |
|---|---|---|---|---|
| Alternative 1 | 97.4 | 15.65 | 76.5 | - |
| Alternative 2 | 45 | 8.50 | 86 | 83.4 |

E.2.5 From the above data, Alternative 2 would seem to offer the best design. The required length of stilling basin is 54% less, and the required tailwater depth is 46% less than for Alternative 1. Also

the energy dissipated is greater for Alternative 2, and the jump developed, although weak, should be less susceptible to tailwater fluctuations. A further extension to the design of Alternative 2 might be to construct a depressed stilling basin to act as a stilling pool. The floor of the stilling basin could be constructed below the original ground level by an amount of equalling the difference between the required tailwater depth and the initial depth of flow, i.e. (8.50' - 3.05') = 5.45 feet, say 6.00 feet.

E.2.6 Required height of sidewall of the spillway chute and stilling basin may be estimated from conclusions made in PARAGRAPH 2.25. From there, $S_m = h_s/d_c = 2.25$, so that $h_s = 2.25\ (5.34) = 12$ feet. Therefore, the height of sidewalls should be about 12 feet above the tread of each step.

E.2.7 Choosing Alternative 2, design dimensions for a spillway comprised of a cascade on the chute for energy dissipation, are shown in FIGURE E-4.



Scale · 1" = 30'

FIGURE· E· 4 CANAL DROP DESIGN USING CASCADES